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Handbook of Sonar Transducer Passive Materials

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Difficulties in the engineering applications of elastomeric materials in sonar transducers are discussed. Factors in the compounding and processing of elastomeric materials which affect end-product performance are also discussed.

Dynamic mechanical properties of a number of elastomeric materials are graphically presented. Appropriate relationships for calculating such parameters as the sound speed,

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20. ABSTRACT (Continued)

attenuation, and loss factor from these curves are given. Compa... ...cipes and cure conditions for the elastomers are included, as well a phye... stati.. pr ties. References to standard test methods (ASTM) are included here appli...ue. Indices containing names of suppliers of elastomeric materials and hesives, as well as generic and tradename cross-indexing, are also incorporated into the handbook.

Additionally, a section on transducer coupling fluids is included in the handbook. This includes fluids currently in use, as well as those liquids being considered for future use. Physical properties of interest such as dielectric constant and electrical resistivity as well as thermodynamic properties (where available), are included.

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PREFACE

Elastomer compounds and fill-fluids are widely used in the construction of sonar systems. However, the mechanical, physical, and acoustic properties of these materials are largely uncharacterized or are widely distributed throughout engineering and scientific literature. The objective of this handbook is to collect and collate information on the static, dynamic, and acoustic properties of present and potential passive sonar materials in a format suitable for the use of transducer design engineers.

Static properties of interest for elastomers include tensile strength, elongation, volume resistivity, dielectric constant, thermal expansivity, water permeability, density, hardness, and chemical compatibility. Dynamic mechanical properties of interest are the dynamic bulk modulus (K^*), the dynamic longitudinal modulus (M^*), the dynamic Young's modulus (E^*), and the dynamic shear modulus (G^*). Modulus information contained in this handbook is taken largely from literature sources. The format chosen for this presentation of modulus information is based upon the Williams-Landel-Ferry equation, which has been used extensively for viscoelastic materials for a number of years.

A section on acoustic coupling fluids is also included in the handbook. This includes fluids which are currently in use, as well as those liquids being considered for future use. Physical properties of interest, such as dielectric constant and electrical resistivity (as well as thermodynamic properties) where available, are included.

This handbook is not intended for the uninitiated. A knowledge of basic theory of material properties is desirable. Familiarity with sonar technology as it pertains to use of materials is also advantageous. However, we have tried to provide sufficient references to relevant topics, so that the reader may further investigate any areas with which he may not be fully familiar.

HANDBOOK OF SONAR TRANSDUCER PASSIVE MATERIALS

I. INTRODUCTION

A. Scope of the Handbook

Passive sonar transducer materials such as elastomers and fluids are widely used in the construction of sonar systems, and their applications are continually becoming more complex. The various applications include transducer boots, encapsulating compounds, acoustic windows, isolation spacers, sound absorbers or transmitters, insulation, and O-rings. Operating conditions may vary over large ranges of frequency, temperature, and pressure; in fresh or salt water; and exposure to many different organic and inorganic fluids. The materials may be cycled through frequency, temperature, and pressure ranges or deployed permanently at some position. Ideally, the operational lifetime should be long.

The designer attempts to satisfy the design specifications by choice of materials with properties compatible with these specifications. The decision usually relies heavily on documented material properties that usually are not complete. One problem is that the properties are a function of frequency, temperature, pressure, curing time and temperature, additives, compounding methods, and sample shape. Another problem is that the existing data are located in diverse publications or have not been published.

The objective of this handbook is to collect information and data related to the various types of elastomers used in sonar systems. It is intended to assist those individuals concerned with the application of elastomeric materials in designing or modifying sonar systems.

The elastomers considered in this handbook include those currently in use, if the data are available. Also, many materials are included that may be useful for future applications. General properties are listed in Section III and are defined in the Glossary. References to standard test methods for these properties are included where applicable.

Recipes, or methods of formulation of elastomers, are included in Section III where information was available.

Appendices are also included for listings of the various types of elastomers and cross-referencing the trade names, generic names, and manufacturers.

The field of elastomer technology is so diverse that the data included here are of necessity not complete. As more data become available, applicable supplements to this handbook will be issued.

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B. Problems of General Consideration

A number of general properties are of interest to designers. The nonacoustic properties include physical, chemical, and electrical properties of the component materials. In many instances, these properties are more important to efficient system operation and reliability than the acoustic properties. For example, water permeability of the transducer boot material is extremely valuable information--particularly if lithium sulfate is being utilized as the transduction material.

This is illustrated in Fig. 1. The hydrophone shown is a USRD type H52. It is an underwater sound measurement standard for use in the frequency range 20 Hz to 150 kHz and can be used to a depth of 5200 m. Its operating temperature range is 0 to 35°C.

Eight lithium sulfate crystals mounted on rubber supports in a castor-oil-filled, butyl-rubber boot comprise the sensitive element of the hydrophone. A solid state preamplifier within the transducer housing provides the proper input and output electrical impedances and a 10-dB voltage gain. A 23-m length of neoprene-covered cable is normally used with the hydrophone. The typical free-field voltage sensitivity (FFVS) of the H52 hydrophone is shown in Fig. 1c.

The choice of butyl rubber for the acoustical boot of this hydrophone is largely a consequence of the fact that the water permeability of most butyl-rubber compounds is about one-twentieth to one-fortieth that of natural rubber, neoprene, polyurethane, Hypalon®, styrene-butadiene (GRS), polyvinyl chloride, or nitrile elastomers. A disadvantage of using butyl rubber is the mismatch in acoustic impedance that occurs as the water becomes colder. This is due to the fact that there is a relatively large increase ($\simeq 300$ m/s for a butyl gum in going from 25 to 5°C) in sound speed in the butyl and a decrease in the sound speed in seawater.

The severity of the acoustic impedance mismatch in a transducer will be influenced by several factors. At audio and low-ultrasonic frequencies, the elastomer thickness is small compared to a wavelength of sound. A symmetrical geometry between the sensor and the acoustic window will help to alleviate the problem of impedance mismatch. In the case of butyl [1], it has been found that butyl boots with a thickness of 6.35 mm do not seriously affect the response or directional characteristics of a hydrophone at low frequencies (see Figs. 2 and 3), provided that the upper frequency range is restricted to 40 kHz and a uniform cross section is maintained in the acoustic window.

Other problems of practical consideration in the choice of transducer materials include ease of molding or bonding to metals and a choice of the correct primer method. General information on primer methods is contained in Section V.

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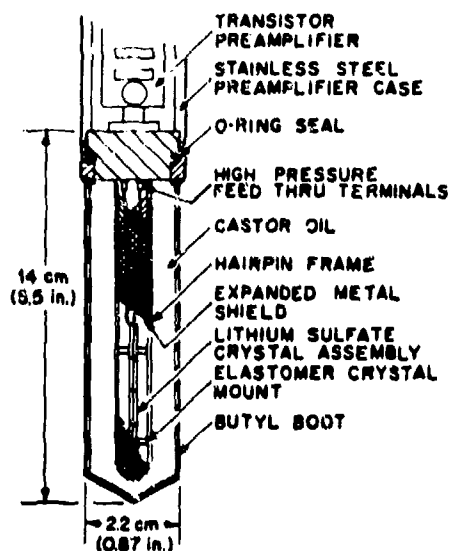
Fig. 1a. Construction details of H52
hydrophone.
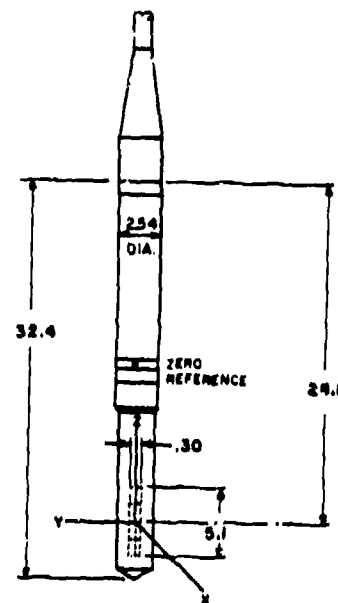
Fig. 1b. Dimensions(cm) and orienta-
tion of H52 hydrophone.
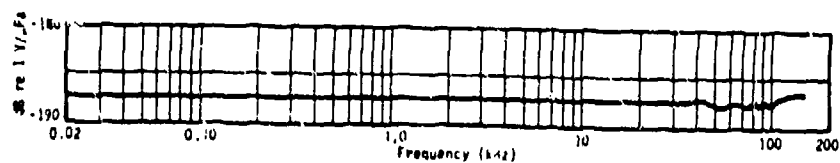
Fig. 1c. Typical free-field voltage sensitivity, type H52 hydrophone
open-circuit voltage at end of 23-m cable.

(References 1 and 81)

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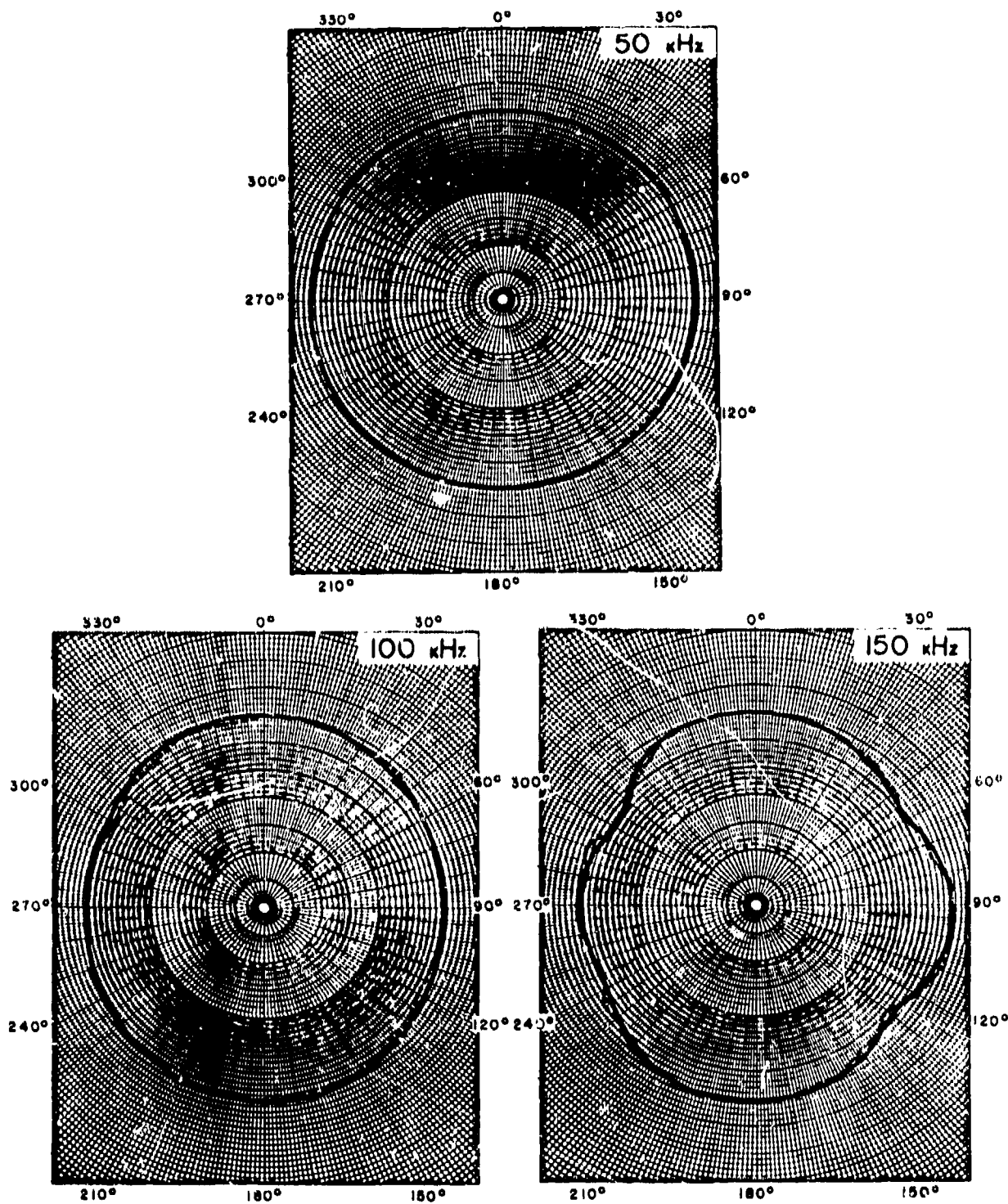
Figure 2—Typical directivity patterns in the XY plane, for a USRD type H52 hydrophone. Dashed lines indicate effect of a protective wire guard around the hydrophone. Center to top of grid, each pattern, equals 50 dB.

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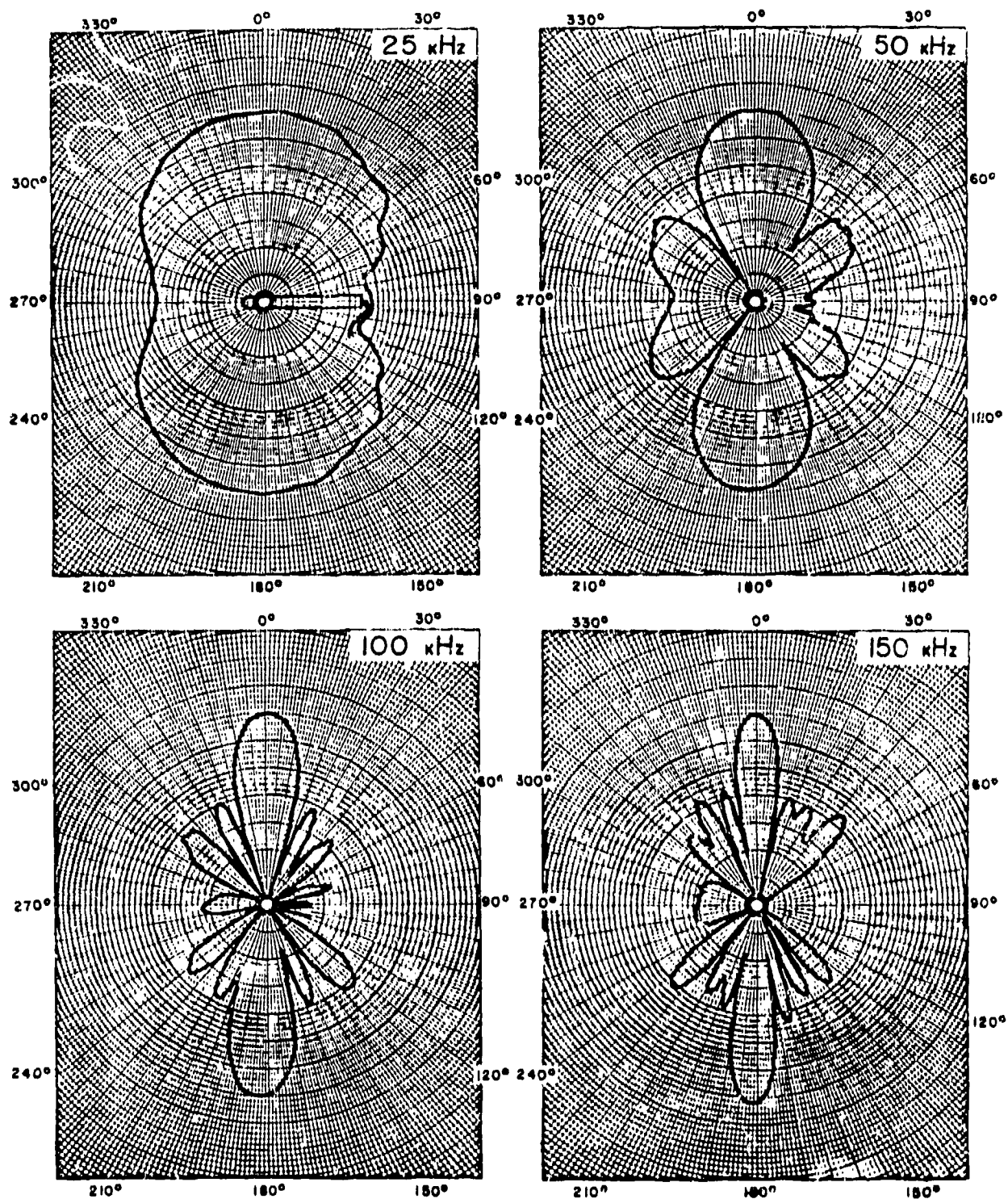
Figure 3 – Typical directivity patterns in the XZ plane, USRD type H52 hydrophone.
Center to top of grid, each pattern, equals 50 dB.

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Free sulfur content of the elastomer used should be minimized by proper curing because it tends to react with any silver present in the electrodes of the transducer. Certain types of elastomers are amenable to tests for free sulfur (ASTM D-297), so that the correctness of the rubber cure with regard to minimizing the free sulfur content can be monitored.

If the elastomer is to provide electrical insulation, as well as being a mounting material for a sensor element, then it should have a high electrical resistivity as well as good acoustic properties.

The pitting and corrosion of metals used in the construction of transducers may also be a source of concern. Tables 1 and 2 (taken from Ref. 1) give typical corrosion rates and pitting characteristics of various metals and alloys in seawater, as well as mechanical and physical properties of various alloys. A more extensive compilation of information on corrosion of materials in a marine environment is contained in Ref. 2, along with additional references to the topic. The best method of corrosion protection is to coat the metal with an elastomer. The metals to be used can then be selected to provide the best strength-to-weight ratio for a particular application.

C.   Compounding of Elastomers

Designers of sonar systems incorporating component materials based on polymeric systems must consider a variety of parameters that can alter material response and affect product performance. Figure 4 summarizes some of these interactive factors. There is a definite cause-and-effect relationship between these factors and product performance.

Of the many factors significantly affecting end-product performance, the fabricating process and processing conditions are two of the most important. The compounding of rubber is as much an art as it is a science, and the ability of the compounder to provide a stock with the appropriate physical properties for a given service application is important.

References 3, 4, and 5 discuss some of the factors involved in the compounding of rubber articles. The ingredients involved in the compounding of elastomers can be divided into the elastomer gum stock, the cure system, filling agents, antidegradants, processing aids and softeners, and various miscellaneous ingredients [6]. A brief discussion of the function of each of these follows.

1.   The Elastomer Gum Stock

In many commercial applications, the selection of the elastomer stock to be used is based on cost. The compounder will normally try to use the lowest priced polymer that will provide the required properties for a specified service application. The properties of any elastomer type may be varied widely by compounding to conform to specific needs--such as

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Table 1* – Typical Corrosion Rates and Pitting Characteristics
of Various Metals and Alloys in Seawater

Material	Corrosion rate (mean range)	Resistance to pitting	Typical rate of penetration in pits
70-30 Cu-Ni[a]	0.2-3.8×10^{-2} mm/yr 0.1-1.5 mils/yr	Good	2.5-13×10^{-2} mm/yr 1-5 mils/yr
Copper[a]	1.2-7.6×10^{-2} mm/yr 0.5-3.0 mils/yr	Good	15-30×10^{-2} mm/yr 6-12 mils/yr
Ni-Al Bronze[a]	2.5-30×10^{-2} mm/yr 1.0-12 mils/yr	Good	5-23×10^{-2} mm/yr 2-9 mils/yr
Monel 400[a]	b	Fair	13-38×10^{-2} mm/yr 5-15 mils/yr
316 Stainless[a]	b	Fair	178×10^{-2} mm/yr 70 mils/yr
Armco 22-13-5 Stainless[c]	Not available	Good	Unaffected after 9 mo in quiet sea water
Berylco 717C[d]	Reported by manufacturer to have virtually the same corrosion characteristics as Std 70-30 Cu-Ni alloy		
7075-T6 Aluminum[e]	b	Fair	28-51×10^{-2} mm/yr 11-20 mils/yr Always needs protection
6061-T6 Aluminum[e]	b	Moderate	13-25×10^{-2} mm/yr 5-10 mils/yr May need protection
5086-H34 Aluminum[e]	b	Excellent	$<2.5 \times 10^{-2}$ mm/yr <1 mils/yr Usually unprotected
5083-0 Aluminum[e]	b	Excellent	$<2.5 \times 10^{-2}$ mm/yr <1 mils/yr Usually unprotected

[a] H. H. Uhlig, *Corrosion Handbook* (John Wiley & Sons, New York, 1948).

[b] Characteristic form of corrosion makes over-all weight loss data meaningless, since failure occurs by pitting.

[c] Armco Product Data S-45 (June 1970).

[d] The Beryllium Corporation, Bulletin No. 4100 (1966).

[e] R. E. Groover, T. J. Lennox, Jr., and M. H. Peterson, "Characterization of the Corrosion Behavior and Response to Cathodic Protection of Nineteen Aluminum Alloys in Sea Water," NRL Memorandum Report 1961, Jan 1969.

*Taken from Ref. 1

Table 2* – Some Mechanical and Physical Properties
of Various Alloys

Alloy	Ultimate tensile strength MN/m² / ksi	0.2% Yield MN/m² / ksi	Elongation in 5 cm (2 in.) (%)	Modulus of elasticity 10^3MN/m² / 10^3ksi	Density 10^3kg/m³ / lb/in³	Strength/wt (yield/dens) 10^2m / 10^3in.
Berylco 717C (aged)	758.4 110	517.1 75	7	152 22	8.91 0.322	59.2 232
Std 70-30 Cu-Ni MIL-C-20159-1	413.7 60	220.6 32	20	152 22	8.91 0.322	25.3 99
5% Ni-Al Bronze MIL-B-16033-1(4) (heat treated)	758.4 110	413.7 60	5	131 19	7.72 0.279	54.7 215
316 Stainless MIL-S-18262-3	482.6 70	206.8 30	30	200 29	8.02 0.290	26.3 103
Ni-Al Bronze MIL-B-21230-1	586.1 85	241.3 35	15	131 19	7.53 0.272	32.7 129
Mn-Ni-Al Bronze MIL-B-21230-2	620.6 90	275.8 40	20	124 18	7.53 0.272	37.4 147
Armco 22-13-5 Stainless[a]	827.4 120	448.2 65	45	200 29	7.89 0.285	57.9 228
7075-T6 Aluminum	572.3 83	503.3 73	11	71.7 10.4	2.80 0.101	183.4 722
6061-T6 Aluminum	310.3 45	275.8 40	12	68.9 10.0	2.71 0.098	103.8 408
5086-H34 Aluminum	324.1 47	255.1 37	10	71.0 10.3	2.66 0.096	97.8 385
5083-O Aluminum	289.6 42	144.8 21	22	71.0 10.3	2.66 0.096	55.5 218

[a]Annealed at 2050°F (1121°C) and water quenched.

*Taken from Ref. 1
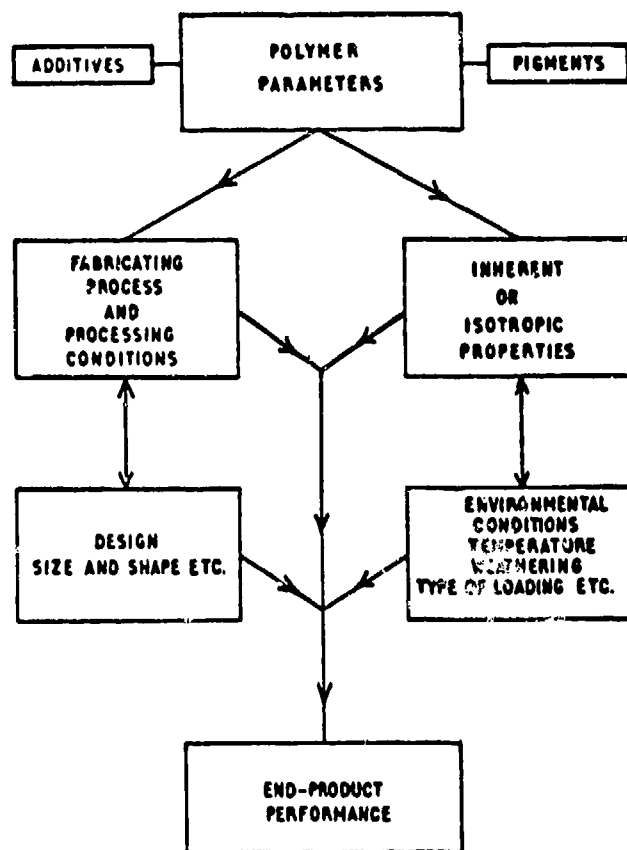
Fig. 4 — Interactive factors controlling
product performance

water resistance, dielectric properties, moduli, and so forth. This application-oriented approach requires that the compounder know what properties need to be optimized. In limited-use areas, cost may be a secondary factor since availability of compounds meeting the requirements may be small.

Ease-of-mixing and subsequent processing are also important considerations in the choice of a polymer base. Table 3 summarizes the factors involved in the choice of a gum stock.

Table 3* - Factors Involved in the Selection of Polymers

Cost

Ease of Mixing

Strength Requirements

Acoustic Properties

Water Permeability

Elongation Requirements

Modulus or Stiffness Requirements

Oil Resistance Requirements

Low Temperature Requirements

Fatigue Requirements

Moldability or Flow

Tack

Amenability to Various Cure Systems

Tear Resistance

Set or Stress Relaxation

Service Temperature

Dynamic Properties (Hysteresis, Damping, Resilience, etc.)

Flammability

Chemical Resistance

*Taken from Ref. 6

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2. The Cure System

The cure system for an elastomer may consist of any or all of vulcanizing agents, cure accelerators, and accelerator activators and retardants. The most commonly used vulcanizing agents are sulfur and sulfur-bearing compounds. These include such compounds as selenium diethyldithiocarbamate (Selenac), tellurium diethyldithiocarbamate (Tellurac), different types of thiuram disulfide compounds (Tuads), and di pentamethylene thiuram hexasulfide (Sulfads). Organic peroxides such as dicumyl peroxide (Dicup) and 2,5-bis (tert-butyl peroxy)- 2,5 dimethyl hexane (Varox) are also used as vulcanizing agents. Selenium (Vandex) and tellurium (Telloy) also find some use.

A large number of substances containing nitrogen and/or sulfur have been investigated at one time or another as cure accelerators. Organic compounds currently used as cure accelerators are generally thiazole types, sulfenamide types, dithiocarbamate types, and thiuram types. For a discussion of the properties of these compounds, the reader should consult Refs. 3, 4, and 5.

Several different types of compounds may function as accelerator activators. Zinc oxide is necessary to activate the types of cure accelerators previously mentioned. It is normally added in 3 to 5 parts by weight on the rubber, and should be low in lead content. A fatty acid, such as stearic, is a useful cure accelerator. The fatty acid is believed to react with the zinc oxide present to form a rubber-soluble zinc soap under curing conditions. This soap, in turn, reacts with the accelerator to allow it to exert its full effect.

Certain alkaline substances, such as litharge (PbO), magnesia (MgO), certain types of calcium carbonates, furnace blacks, and amines, will act to accelerate vulcanization. Materials of an acidic nature, if present in sufficient quantity, will tend to retard curing. Thus, benzoic and salicylic acids and N-nitroso diphenylamiene are used for scorch control in some hot-processing stocks.

3. Filling Agents

For many service applications, it is necessary to incorporate into the rubber relatively large amounts of reinforcing materials to increase its hardness, stiffness, tensile strength, and resistance to abrasion and tear. These filler materials include various carbon blacks, zinc oxide, fine-particle calcium carbonates, hard clays, and hydrated silicon compounds such as silicon dioxide.

The use of these filler materials in compounding requires a knowledge of properties obtained through their use and how they affect processing and rate of cure [6, 8, 9]. Carbon black is a commonly used filler, and has been the most thoroughly investigated. The classification system for carbon blacks used in rubber systems is specified in ASTM D1765-77a. Effects of carbon black type, loading, and processing conditions on dynamic properties of vulcanizates have been conducted [10-17]. Relatively little information is available [18-20] for comparison of dynamic and electrical properties of individual elastomers at equal loading of the same black.

The degree of effectiveness of carbon black as a reinforcing agent depends primarily upon four factors [4]: 1) particle size of the carbon black, 2) structure of the carbon black, 3) surface chemistry of the carbon black, and 4) degree of dispersion of the carbon black in the rubber.

Carbon black particles will typically have a size in the range from 100 to about 700 Å (1 Å = 10^{-8} cm). Smaller sized particles typically give a greater degree of reinforcement and greater hysteresis loss upon flexure. ASTM D-1151-74 may be used to test the pellet size distribution of carbon blacks.

The term "structure" as applied to carbon blacks is now taken to mean the existence of chain-like aggregates of carbon black particles in the rubber mix after the black has been dispersed [4]. The stiff paste or Gardner oil absorption test may be used to judge the extent of structure [4]. The existence of structure in oil-extended SBR, in particular, tends to give a high modulus after vulcanization and a low swell upon extrusion.

The pH of the carbon black will also have an effect on vulcanization. Acidic channel blacks will tend to retard cure, while alkaline furnace blacks will act as cure accelerators. ASTM D1512-75 gives procedures for establishing carbon black pH values.

Adsorption of accelerator compounds onto the carbon black surface is sometimes a problem. This lowers the amount of accelerator available for the vulcanization reaction. The DPG adsorption test [4] may be used to monitor this.

Good dispersion of the carbon black filler is essential if the properties of the rubber are to be optimized. Historically, the most frequently applied method of examination for carbon black dispersion has been to examine the cut or torn surface of the vulcanizate. If the surface is dull and rough, poor dispersion is indicated. A smooth and glossy surface implies good dispersion.

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More quantitative variations of this technique involve photographic procedures based on numerical standards (ASTM D-2663, Method A) and light microscope methods (ASTM D-2663, Method B). An automated procedure recently reported in Ref. 21 may be used to check carbon-black dispersion in both cured and uncured rubber stocks in as little as four minutes.

If high volume resistivity of the rubber is an important criterion, then care should be taken in the use of carbon-black filler. Certain types of blacks (such as acetylene blacks, several grades of furnace blacks, and one channel black) will give conductive rubbers. If a really high volume resistivity is necessary, the design engineer should make this point clear to the rubber compounder.

4. Antidegradants

Elastomeric materials tend to undergo changes in properties with the passage of time. Oxidation by atmospheric oxygen is the major cause. The extent of aging will be influenced by a number of internal and external factors. The internal factors include the type of elastomer, the cure system, and antidegradants. The article by Parks and Spacht [22] is an excellent discussion of the use of antioxidants in rubber compounding. Much of the discussion that follows is abstracted from this.

The chemical nature of the elastomer itself will influence, to a certain degree, the aging characteristics of a rubber article. The more highly saturated polymers (such as butyl and EPDM) exhibit better resistance to aging than elastomers (such as natural rubber and SBR). This is probably related to the fact that oxidation of rubber is primarily a free-radical process.

Table 4, taken from Ref. 22, lists the general classes of antidegra-dants and their properties and uses. The primary function of these compounds is to extend the useful service lives of elastomeric materials. The elastomer must be protected both during storage and processing and after vulcanization.

Materials used for protection during storage and processing are referred to as stabilizers. Stabilizers may be destroyed or rendered ineffective during vulcanization; thus, they do not always serve as antioxidants in the vulcanized product. The minimum amount of stabilizer necessary is normally added, with the assumption that additional anti-oxidants will be added during compounding to give the desired aging characteristics. Proper stabilization is important because oxidative degradation of the polymer during storage cannot be compensated for through the use of additional antioxidants during compounding.

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Table 4* - General Classes of Antioxidants and Antizonants-Properties and Uses

Antioxidant Class	General Properties	Recommended Uses
Monohydric phenols	Low Cost, Minimum dis-coloration and stain-ing, Selected ones F and DA approved, High Solubility in rubber, No effect on cure rate	Polymer Stabilization, Carcass and sidewalls, Light colored mechani-cal goods
Bis-phenols	Some discoloration and staining, Selected ones F and DA approved, Low volatility, No affect on cure rate	Latex stabilization, Light colored mech-anical goods, Polymer stabilization
Polyphenols	Slight discoloration and staining, Low vola-tility, Very persistent, Some are F and DA approved	Latex stabilization, Latex compounding, Rug backing, White sidewalls
Dihydric phenols	Mostly hydroquinone de-rivatives, Considerable discoloration	Stabilizers for stereo rubbers, Nitrile rubbers
Phenolic sulfides	Some color problems, Low Volatility	**Latex** compounding, Foam, Rug backing
Phosphites	Low cost, Excellent color	Polymer stabilization, Suppress gel formation
Mixed phenol phosphites	Combined properties of each, Autosynergistic	Polymer stabilization, Latex compounding
Thiodipropiona s	Synergistic with phenols, Good for polyolefins, Poor antioxidant by itself	Not recommended for compounding stocks
Alkylated diphenylamines	Slight discoloration and staining, Negligible effect on cure, Better than some phenols	NBR Stabilization, Latex compounding, Limited use in rubber compounding
Alkoxydiphenyl-amines	Discoloring and volatile, Good antiflex cracking agents, Slight antiozonant activity	Component in some antioxidant blends

(continued)

Table 4 (continued)

Antioxidant Class	General Properties	Recommended Uses
Acetone diphenyl-amine reaction products	Active antioxidants, Good flex cracking agents, Partially volatile	Polymer stabilization, Antioxidant for general compounding
Aryl-napthylamines	Active antioxidants, Moderate volatility, Negligible effect on cure, Severe discoloration, Toxicity questionable	Polymer stabilization, Mechanical goods, Tires
Polymeric dihydroquinolines	Very low volatility, Good heat resistance, Moderate discoloration	Heat resistant stocks of all types
N,N'-dialkyl-p-phenylenediamines	Low volatility, Discoloring and staining, Increase cure rates, Toxicity varies with mol. wt., Easily oxidized	Potent antiozonants, Excellent for short term ozone resistance
N-alkyl-N'-phenyl-p-phenylene-diamines	Volatility and toxicity depend on size of alkyl groups, Excellent antioxidants, Excellent antiflex cracking agents, Discoloring and staining, Activate the cure	Antiflex cracking agents; Metal deactivators; Used in treads, sidewalls, and mechanical goods, Polymer stabilization
N,N'-diaryl-p-phenylenediamines	Low volatility and toxicity, Limited solubility, Excellent antioxidants, Excellent antiflex crack agents, Discoloring, Low staining, Negligible effect on cure	Polymer stabilization; Used in treads, sidewalls, and mechanical goods
N,N'-di-β-naphthyl-p-phenylene-diamine	Very low solubility and volatility, High melting point, Good antioxidant, Metal deactivator, Some discoloration, Negligible staining, Toxicity questionable	Used in antioxidant blends, Foam, Rug backing, Heat resistant stocks

*Taken from Ref. 22

There are a number of factors external to the polymer itself that affect the aging of elastomers. These factors are heat, oxygen, fatigue, metal catalysts, and ozone.

Generally, heat is an important factor in rubber aging in cases where elevated temperatures are routinely encountered. This is due to the fact that a 10°C increase in temperature approximately doubles the rate of oxidation. A number of tests (ASTM D573-67, ASTM D865-62, ASTM 1870-68) are useful in studying the effects of heat on rubber in accelerated aging. The accelerated tests are helpful in that they show general trends. In many cases, however, it is difficult to correlate results between natural and accelerated aging. For all practical purposes, heat aging should not be a source of concern in elastomers used in sonar since elevated operating temperatures will seldom be encountered.

The effect of oxygen on an elastomer will depend upon the type of rubber and the aging conditions to which it is subjected. In general, two competing processes will take place: chain scission and cross-linking. Chain scission, as the name implies, results in the breaking of bonds. Cross-linking results in the formation of new bonds, as a result of sites of unsaturation present in the elastomer.

The net effect of chain scission is a reduction in tensile strength. Natural and butyl rubbers and polyisoprene are more susceptible than other types of rubbers to chain scission.

Cross-linking typically results in a loss of elasticity that is characterized by an increase in modulus or hardness or a decrease in elongation. Neoprene and butadiene rubbers such as polybutadiene, SBR, and NBR are most susceptible to cross-linking. Prevention of hardness due to cross-linking is difficult, as antioxidants have little effect in protecting butadiene rubbers against cross-linking. P-phenylenediamines appear to offer some protection [22].

ASTM D572-73 is a useful test method for accelerated oxidation testing.

Repeated extensive, compressive, and bending forces on an elastomer may lead to a serious reduction in its useful service life. The prevention of cracking during flexing is an important use of antioxidants in compounding. One of the most important types of fatigue failure, flex-cracking, involves both a mechanical fatigue and a heat build-up during flexure that acts to accelerate oxidation. For this reason, antioxidants for heat resistance are also used to prevent dynamic fatigue. The N-alkyl-N'-phenyl-p-phenylenediamines are among the best flex-cracking antioxidants [22].

ASTM D430-75 and ASTM D623-67 are recommended procedures for testing the effects of fatigue of elastomers.

Trace amounts of transition metal ions such as copper, iron, and manganese may have an adverse effect upon the service life of elastomers. This is due to the fact that these ions exert a catalytic effect on free radical generation in the oxidative decomposition of rubber [22,23].

These metals may be present in the elastomer itself, as trace impurities in mineral fillers, or introduced from processing equipment. Chelating agents are normally used to protect raw polymers but have not found extensive use in compounded stocks. The p-phenylenediamenes, commonly used antioxidants, are also effective chelating agents. The process of vulcanization itself also offers some protection, as the metals are converted to insoluble sulfides during the cure. Reference 5 gives chemical tests for detection of copper and manganese in elastomers.

Exposure of an elastomer to light in the ultraviolet wavelength region may lead to deterioration by catalyzing the auto-oxidation of the rubber [22]. White or light-colored rubbers may discolor to an objectionable degree or develop a brittle surface layer that will shatter upon flexing.

This condition is known as crazing. It can be prevented by adding carbon or ultraviolet (UV) absorbing materials to the rubber. Since crazing is a surface effect, the UV absorber must bloom to the surface of the rubber to be effective. Materials such as nickel dibutyldithiocarbamate and O-hydroxybenzophenone derivatives have been used as UV absorbers [22, 24]. Certain waxy materials (such as paraffin, syncera wax, ozokerite, and others) are often added in excess of their solubility in rubbers. These materials will bloom to the surface after vulcanization, and the resulting film will protect the rubber from crazing.

ASTM D1148-77 describes a light discoloration test for light-colored rubbers using a source of UV radiation. ASTM D750-68 describes equipment procedures for accelerated aging tests using sample exposure to calibrated light sources.

The effect of ozone on rubbers is also typically a surface effect. The mechanism of the reaction of ozone with rubbers is believed to proceed through ozonolysis [22,25]. The ozonide intermediates decompose to cause chain scission, resulting in the formation of cracks in a stressed rubber. The characteristic feature of ozone cracking is that the cracks are at right angles to the direction of strain. In unstressed rubbers, ozonolysis will typically give a bloom-like appearance called frosting.

The formation of cracks is dependent upon the degree of elongation of the elastomer. The exact degree of elongation necessary for cracks to begin forming will depend upon the type of rubber and compounding ingredients, usually in the range of 5 to 10 percent. At a high degree of elongation, the cracks become more numerous and smaller. At a low elongation, large, deep cracks are found. It is these larger cracks that typically lead to rubber failure [22].

The type of rubber will also affect cracking. Natural rubber forms many fine cracks, while SBR forms large cracks. Neoprene rubbers display much better ozone resistance than SBR or natural rubbers.

Protection against ozone often involves surface coatings or waxes that bloom to the surface of the rubber to form a protective film. Certain combinations of polymers also give good ozone resistance, such as nitrile rubbers with poly(vinylchloride) [22].

ASTM 1149-77, ASTM D1171-68, and ASTM D3395-75 give recommended procedures for evaluation of ozone attacks on elastomers.

For a more detailed discussion of aging in elastomers, the reader should consult Refs. 3, 4, 5, and 22. Reference 26 also contains a useful compilation of results of aging tests for different types of elastomeric materials. References 4 and 5 contain information on commercial antioxidants and suppliers. Table 5 summarizes the weathering characteristics of various types of elastomers.

5. Processing Aids and Softeners

Various materials are usually added to raw rubber stocks to facilitate mechanical breakdown and ease of processing during compounding. These are softeners, processing aids, plasticizers, extenders, and tackifiers.

The distinction between some of these materials is nebulous. Typically, oils added in small amounts tend to act as softeners, while larger amounts are used as extenders. Mineral oil is widely used as an extender for SBR. Petroleum oils find extensive use as softeners and plasticizers. The chemical composition of these oils is quite complex. Reference 4 discusses the main components normally found in these oils, and ASTM D 2007-75 specifies a procedure for identifying the characteristics groups in petroleum processing and extending oils. Various vegetable oils, coal tar, petroleum residues, and natural and synthetic resins are also used in compounding.

Plasticizers are useful in several aspects of compounding. They permit rapid incorporation of fillers and other ingredients during the mixing cycle. They reduce internal friction in calendaring and extrusion, thereby helping to minimize scorch. Plasticizers and softeners are also useful in compounding for applications that may require low modulus and hardness.

Tack is the tendency of two pieces of rubber to stick together, while stickiness is the tendency of rubber to stick to unlike materials such as mill rolls [6]. The rubber compound should have sufficient tack for building operations but not enough stickiness to interfere with other processing steps. Tack typically decreases with increasing loading and dilution of the base polymer. Methods of measurement for tack and stickiness may be found in Ref. 27.

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Table 5 - Aging Properties of Different Types of Elastomers

Elastomer Designation	Ozone Resistance	Sunlight Resistance	Weather Resistance
Butadiene (BR)	*Fair	Fair	*Fair
Butyl (IIR)	Good	Good	Excellent
Chlorosulfonated Polyethylene (Hypalon)	Excellent	Excellent	Excellent
Ethylene Propylene Diene (EPDM)	Excellent	Excellent	Excellent
Fluorocarbon Rubbers (CFM)	Excellent	Excellent	Excellent
Natural Rubber (NR)	*Fair	Fair	Fair
Neoprene Rubber (CR)	*Excellent	Excellent	Good
Nitrile Rubber (NBR)	Fair	Fair	Fair
Polysulfide Rubber (T)	Excellent	Excellent	Excellent
Silicone Rubber (MQ)	Excellent	Good	Good
Styrene-Butadiene (SBR)	*Fair	*Fair	Fair
Urethanes (U)	Excellent	Excellent	Excellent

*Requires special compounding

6. Miscellaneous Ingredients

This category is a catch-all for several different types of substances. These include inert fillers and diluents (such as soft clays, whiting, talc, or mineral rubbers). Pigmenting materials, deodorants, abrasives or other substances are also sometimes added during compounding, depending upon the final service application of the elastomers.

D. Processing of Elastomers

A complete treatment of elastomer processing would include a discussion of mixing, calendaring, and extruding. Since these areas lie more within the province of the rubber compounder than the design engineer, they are not included here. The reader who is interested in these topics should consult Refs. 3, 4, and 5. For the sake of brevity, the discussion here is limited to vulcanization and molding of elastomers.

1. Vulcanization

In order to convert most natural and synthetic rubbers to a finished state, it is necessary to apply heat in some form or other. This operation is known as vulcanization or curing. It may be accomplished in a number of different ways, depending upon the size and structure of the finished product and the elastomer being processed. These include autoclave vulcanization in open steam, autoclave vulcanization under water, fluid-bed vulcanization for extruded products, and press vulcanization. References 4 and 5 discuss all these methods. Since the construction of transducers normally involves the molding of articles by compression, transfer, or injection methods, the discussion in this handbook is directed primarily towards press curing.

In order for the finished rubber product to exhibit the desired chemical and physical properties, it must reach the proper state of cure. Properties such as tear and abrasion resistance, cracking resistance, hardness, flexing properties, modulus, and others are all affected by the state of cure. An interesting discussion of this can be found in Chapters 2 and 3 of Ref. 3.

In order to determine what is an "optimum" cure, it is customary to make a series of cures (usually for different times at the same temperature) and to measure the physical properties of the vulcanized product. Various parameters (such as maximum tensile strength, tensile modulus, and ultimate elongation) have been utilized at one time or another as criteria for judgment of optimum cure. The modulus is now generally used.

In order to lessen the time and effort involved in experiments to evaluate the above quantities, a number of instruments have been developed that continuously measure the characteristics of the elastomer while it is being vulcanized. A short description of these, along with references to articles which describe their use, can be found in Ref. 5.

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Two of the more widely used of these instruments are the Monsanto Oscillating Disk Rheometer and the Mooney Viscometer.

The Monsanto Oscillating Disk Rheometer is designed to monitor the curing characteristics as a function of time of a single rubber specimen that is heated and maintained at a constant temperature and pressure during vulcanization. The vulcanizable elastomer is contained in a heated square cavity with a conical disk inbedded in it. The sinusoidal oscillation of this disk exerts a shear strain on the elastomer. The torque necessary to oscillate the disk is directly proportional to the shear modulus of the elastomer. The resistance of the rubber to the oscillating disk is measured by a stress transducer on the torque arm and is plotted autographically to yield a curve of torque vs. time. A complete description of the oscillating disk rheometer and its operation is contained in ASTM D2084-75, along with recommended test procedures. The graph obtained from a rheometer exhibits such parameters as minimum torque, scorch safety, cure rate, and maximum torque. This information is desirable for repeatability of optimum cure from one sample of elastomer to the next.

The Mooney Viscometer is a shearing disk viscometer that may be used as a standard method for determining the viscosity of elastomer materials in the raw or compounded state and for determining the curing characteristics of such materials. The rubber is contained under pressure in a shallow cylindrical cavity. A disk rotating in the cavity provides the shearing action.

ASTM D1646-74 describes the operation of this machine and recommended test procedures. Using an arbitrary set of units under standardized conditions, the viscosity of elastomers (either vulcanizable or unvulcanizable) may be determined over a range of temperatures.

For determining curing characteristics, the viscosity of vulcanizable elastomers is recorded during heating at a given temperature. Minimum viscosity and rate of change of viscosity in specified amounts are used as arbitrary measures of the start and rate of cure. The method cannot be used to study complete vulcanization because it requires the continuous rotation of the disk inside the cavity.

2. Molding of Elastomers

Press curing of an elastomer requires that the compound to be cured flow properly without scorching before the desired shape is reached. The elastomer should also be easily removable from the mold after cure. This requires a proper mold design and the use of mold lubrication.

A commonly encountered problem is porosity in thick articles. This is generally caused by undercuring or by insufficient external pressure during the initial portion of the cure. The thickest portion in the cross section of the finished article should be examined for porosity,

and the cure cycle should be correspondingly adjusted if it is found.
Problems with porosity can usually be solved by use of a more suitable
cure accelerator. If problems with porosity suddenly develop with
elastomers that previously have been satisfactory, then moisture in the
filling agents or improper dispersion of sulfur or accelerators in the
compound should be suspected.

Trapped air inside the finished product is a common fault in many
press cured articles. It may be caused by improper mold design, using an
elastomer that is too soft, or improper filling of the mold before the
cure cycle is started. If possible, injection or transfer molding should
be used to minimize the problem.

3. Compression Molding

Compression molding is the simplest of the rubber molding
processes. The mold is a simple flash type with tapered pins for re-
gistering the two halves of the mold. This is illustrated in Fig. 5a.
An excess of uncured, room-temperature elastomer is placed in the cavity
(or cavities) of the mold. The top is put into place, and the two
halves of the mold are squeezed together between the two heated platens
of a press. As the rubber reaches its softening temperature, it begins
to flow and assume the shape of the mold cavity. The excess elastomer
flows out into the overflow grooves of the mold and is called the flash.
The mold should be designed so that the placement of the flash does not
affect the performance of the finished elastomer product. The rubber
begins to cure as soon as it reaches its vulcanization temperature
(usually near 150°C). The mold should then be left in the press, under
pressure, for the length of time necessary for optimum cure of the
elastomer.

Compression molding is a slow process, since the entire rubber mass
must reach curing temperature before the period of vulcanization begins.
Sufficient time must be allowed to avoid uncured or undercured articles.

4. Injection Molding

Injection molding, as the name implies, involves injecting
uncured, preheated rubber into a closed, heated mold under high pressure.
Injection molding has several advantages over compression molding. It
gives more uniform physical properties of the vulcanizate due to automatic
cure cycling. The finished elastomer product also has better physical
properties because the stock is held at higher temperatures for a shorter
time. Injection molding generally gives better rubber-to-metal bonds than
compression molding.

Injection molding is most useful when medium or high-production
quantities of an article are to be produced. It results in lower labor
costs due to faster cure cycles and the elimination of having to prepare
mold preforms as in compression molding. There is also a savings in raw
materials.
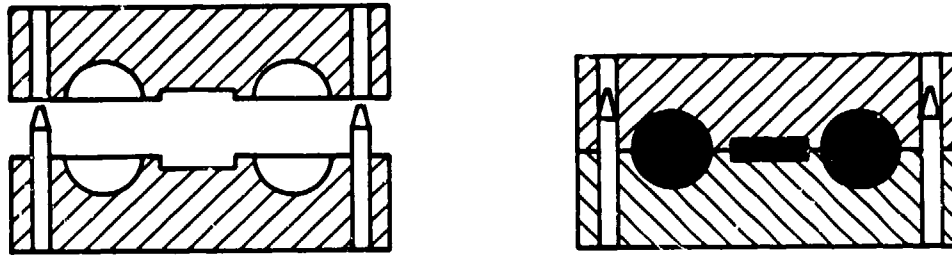
Figure 5a. Compression Molding

Figure 5b. Injection Molding

Figure 5c. Transfer Molding

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5. Transfer Molding

Transfer molding is a variation of injection molding. It is useful in cases where the production volume does not justify the expense of fully automatic injection molding. In transfer molding, the injection feature is built into the mold. The elastomer is placed in a recessed section of the mold, and a plunger forces the stock through a small opening into the mold cavity.

Transfer molding is better than compression molding for the bonding of rubber to smaller delicate metal parts. The closed mold holds the parts in the proper position through the transfer and cure cycle so that there is no chance of parts shifting or being damaged.

Transfer molding is also better than compression molding for making detailed or intricate moldings. This is because the transfer mold maintains constant pressure on the elastomer stock so that it is evenly dispersed throughout the mold. In a compression mold, too much rubber may escape from the overflow grooves, causing incomplete filling of the mold cavity. On bonded parts, this loss of stock would cause a low degree of adhesion. Transfer molding also tends to eliminate any grain effect due to the method of filling the mold cavity, as sometimes occurs in compression molding, with a resultant uniformity of shrinkage in the finished product.

6. Mold Tolerances

Since all rubber shrinks to some extent after molding, it is necessary that the mold designer and rubber compounder estimate the amount of shrinkage and allow for this in the size of the mold cavity. The type of compound; variations in rubber from batch to batch; and variations in cure time, temperature, and pressure will all affect the amount of shrinkage. For this reason, adequate dimensional tolerance in molds must be specified that will cover this inherent variability.

Since rubber deforms, the close tolerances normally specified on metal parts are often unnecessary on rubber parts. The cost and effort of designing molds are also directly related to the tolerances required. In practice, transfer molding will permit a greater accuracy in precision molding than compression molding. Tolerances on rubber-metal parts must be greater than on all-rubber parts. The tolerances should also be greater than that on any individual metal component.

For rubber molded parts, a common starting place for agreement on tolerances is a series of tables prepared by the Rubber Manufacturers Association (RMA). These are published in the RMA Handbook. For those who are interested in consulting these tables but not having them, a copy of the handbook is available upon request from Huntington Rubber Company. The address may be found in Appendix C.

II. APPLICATIONS

Elastomers are characterized by large deformability, low shape rigidity, large energy-storage capacity, high hysteresis, pressure and temperature dependence of density, and large variations of stiffness with temperature, pressure, and frequency. The original properties of elastomeric materials will change when subjected to a service environment. These properties also vary greatly with the methods of compounding and processing.

The engineer or designer must make a selection of an elastomer based on useful service life in the environment to which the sonar system will be subjected. He must also reach a conclusion concerning the material to be used from an analysis of service requirements as related to the elastomer properties. These qualities make the application of engineering analysis extremely difficult. This section is intended to assist the user in obtaining specific elastomeric properties as a function of frequency and temperature at a given pressure from the data shown for the materials.

A. Elastic Moduli

For most applications, it is more convenient to express the elastic properties of a material as an elastic modulus. The elastic properties of materials can be determined from any two of the three standard moduli (bulk, shear, and Young's). Both the real (E', G', M', and K') and the imaginary (E", G", M", and K") components of moduli are given where sufficient data were available. These components may be combined to form the complex moduli values (E*, G*, M*, and K*) as follows:

$$E^* = E' + jE''$$

$$G^* = G' + jG''$$

$$K^* = K' + jK''$$

$$M^* = M'' + jM''$$

The moduli of viscoelastic materials are known to be functions of temperature, pressure, and time. In particular, there is an interrelated dependence upon frequency and temperature of the behavior of viscoelastic materials at a given pressure. If the temperature of a viscoelastic material is increased, its internal molecular arrangement changes to a more mobile configuration and the material becomes more elastic. Conversely, a reduction in temperature causes a reduction in molecular mobility, so that the material stiffens and exhibits glass-like properties.

If an elastomer is maintained at a constant temperature and the stress frequency is increased, a related but inverse phenomenom occurs. For low frequencies, the period of stress is long enough so that the molecules coil

and uncoil. The behavior of the material is therefore rubber-like. At high frequencies, the period of stress is very small so that the material does not completely relax and resembles a glass. Therefore, the correspondence between frequency and temperature of viscoelastic behavior is that a decrease in temperature at constant frequency causes the same change in the dynamic mechanical properties of an elastomer as an increase in frequency at a constant temperature.

Where possible, moduli presented in this handbook have been reduced according to the method of time-temperature superposition [28]. For a complete exposition of the technique and its theoretical justification, the reader should consult Chapter 11 of Ref. 28. This technique allows data, taken over varying ranges of temperature and frequency and at a given pressure, to be graphically represented using a single composite curve. Graphical modulus data presented in Section III are reduced to a reference temperature (T_R) of 10°C and a reference pressure of 0 MPa, unless otherwise specified.

To assist the user in obtaining the value of the depicted modulus from the reduced graphs, the following procedure is required for determinations at frequency, f (Hz), temperature, T (°C), at a given pressure, P (MPa gauge).

1. Calculate log a_T from the equation

$$\log a_T = \frac{-C_1 (T-T_R)}{C_2 + T} , \tag{1}$$

where C_1 and C_2 are constants whose numerical values are given in the log a_T equation for the specific material, and T and T_R are the temperature of interest and the reference temperature of the reduced plot respectively. It should be noted that the form for log a_T is somewhat different than that given in Ref. 28, as the value of T_R has been incorporated into C_2.

2. Determine log ωa_T by adding log a_T to log ω, where $\omega = 2\pi f$. Note that if the determined value of log ωa_T is not within the interval of log ωa_T presented as abscissa, then the value of T selected is not within the range of experimental temperatures from which the composite curve at T_R was produced. The data are not applicable at this temperature, and another temperature must be selected so that log ωa_T is within the defined limits.

3. Read the value for the appropriate modulus corresponding to the value of low ωa_T for the desired pressure, if graphs for more than one pressure are shown.

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For those users of the handbook who are not familiar with the use of Eq. (1), the WLF equation, an example may prove to be instructive. Consider the curve for Nitrile formulation 314-818. Assume that we are interested in the sound speed and attenuation in this material for shear wave propagation at a frequency of 5000 Hz and a temperature of 10°C.

Since 10°C is the reference temperature, log a_T will, of course, be zero. The value of the abscissa at 10°C will simply be log ω, or log 2π + log f (Hz). For 5000 Hz, the abscissa has a value 4.497, and the ordinates have values of 1.50×10^8 Pa and 1.42×10^8 Pa for the real and imaginary components of the shear modulus, respectively. Using Eqs. (9a) and (9b), the calculated sound speed is 447.1 m/s and the attenuation is 28.3 nepers/m.

If a temperature other than 10°C is desired, the value of the abscissa may be easily obtained by calculating log a_T from Eq. (1) and adding the value of log ω for the desired frequency. The modulus values for G' and G" may then be read off the graph.

The relationships shown in Table 6 may be used to calculate other elastic properties from known complex bulk and shear moduli. The user who wishes to work with the respective compressibilities may determine this by inverting the proper complex modulus (see Ref. 28, p. 15).

Table 6 — Relationships of Elastic Properties at Small
Deformations when the Shear Modulus (G*)[1]
and Bulk Modulus (K*) are Known

Property	Relationship
Lame' Coefficient ($\mu*$)	$G*$
Lame' Coefficient ($\lambda*$)	$K* - \dfrac{2G*}{3}$
Young's Modulus (E*)	$\dfrac{9K*G*}{3K* + G*}$
Poisson's Ratio ($\sigma*$)	$\dfrac{3K* - 2G*}{6K* + 2G*}$
Plane Wave Longitudinal Modulus (M*) .	$K* + \dfrac{4G*}{3}$

[1]The asterisk (*) denotes a complex quantity, i.e.
$$G* = G' + jG"$$

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For practical purposes, these relationships are important only when both moduli are of comparable orders of magnitude. In many cases, the experimental uncertainty in the determination of K* will be of about the same value as the value of G*. Thus, the Young's modulus, for instance, will typically be three times the shear modulus for elastomers.

B. Density

The mass per-unit volume as a function of temperature and pressure is required when determining impedance ($=\rho c$), modulus ($=\rho c^2$), and bouyancy. When the data are available, density as a function of temperature and pressure will be given in the form shown below:

$$\rho = \sum_{k=0}^{m} \sum_{\ell=0}^{m} A_{(k + 4\ell)} T^k P^\ell \qquad (2)$$

where $m \leq 3$, A's are coefficients, T is temperature in °C, and P is pressure in MPa gauge.

The present form of the handbook gives density values at ambient pressure and temperature and either linear thermal expansion coefficients in cm/cm/degree or specific thermal expansivities in cm^3/gram/degree.

C. Sound Speed and Attenuation

The speed of sound and acoustic attenuation in a viscoelastic material are functions of frequency, temperature, and pressure. Additionally, the speed and attenuation of an acoustic wave are dependent upon the particular mode of propagation within the material. Shear waves characteristically have smaller speeds and higher attenuations than either bulk or longitudinal waves.

The velocity of a sound wave propagating through a material is usually complex due to dissipative phenomena occurring within the material itself. It is well known that the relation between the velocity for such a wave and the corresponding complex modulus for a given mode of propagation is given by:

$$c^* = (R^*/\rho)^{1/2}. \qquad (3)$$

The modulus and velocity may be expressed in complex form as:

$$R^* = R' + jR'' \qquad (4a)$$

and

$$c^* = c_1 + jc_2. \qquad (4b)$$

Thus,

$$(c^*)^2 = R^*/\rho = (R' + jR'')/\rho \tag{5a}$$

$$= c_1^2 - c_2^2 + 2jc_1c_2 \ . \tag{5b}$$

Separating and identifying real and imaginary parts gives:

$$R' = \rho(c_1^2 - c_2^2) \tag{6a}$$

and

$$R'' = 2\rho c_1 c_2 \ . \tag{6b}$$

Consideration of the behavior of the normal complex exponential form for a progressive wave [29,30] allows us to relate c_1 and c_2 to the observed phase velocity c and the amplitude attenuation constant α by the relations:

$$c_1 = \frac{c}{(1 + \alpha^2 c^2/\omega^2)} \ , \tag{7a}$$

$$c_2 = \frac{\alpha c^2}{\omega} \left[1 + \alpha^2 c^2/\omega^2 \right]^{-1}, \tag{7b}$$

and

$$c^* = c \left[\frac{1 + j\frac{\alpha c}{\omega}}{1 + \frac{\alpha^2 c^2}{\omega^2}} \right]. \tag{7c}$$

Since

$$R^* = R' + jR'' = (c^*)^2 \tag{8}$$

we may use Eqs. (7c) and (8) to solve for the magnitude of the phase velocity and attenuation. Doing so yields

$$c^2 = \frac{2[(R')^2 + (R'')^2]}{\rho\left[[(R')^2 + (R'')^2]^{\frac{1}{2}} + R'\right]} \tag{9a}$$

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and

$$\alpha^2 = \frac{\omega^2 \rho \left[\left[(R')^2 + (R'')^2 \right]^{\frac{1}{2}} - R' \right]}{2 \left[(R')^2 + (R'')^2 \right]} . \tag{9b}$$

Therefore, by inserting the real and imaginary components of the appropriate modulus G, K, or E [as obtained from the master curves in Section III] into Eq. (9), the acoustic speed and attenuation in the material (corresponding to a particular frequency and temperature) may be determined.

D. Mechanical Loss Factor

The real and imaginary components of a dynamic mechanical modulus may also be called the storage modulus R', and the loss modulus R''. the storage modulus is associated with the energy storage and release in a periodic deformation while the loss modulus is associated with dissipation or loss of energy as heat. The ratio of loss modulus to storage modulus is the mechanical loss factor, $\tan \delta$,

$$\tan \delta = \frac{R''}{R'} . \tag{10}$$

If one defines W_s as the maximum elastic energy stored per complete cycle and ΔW as the energy dissipated per complete cycle, then the ratio $\Delta W/W_s$ is a measure of the energy loss or damping. This ratio is known as the specific damping capacity and is related to the mechanical loss factor and the attenuation of acoustic waves.

$$\Delta W/W_s = 2\pi \tan \delta = 2c\alpha/f \tag{11}$$

where c and α are the velocity and attenuation of acoustic waves of cyclic frequency f (Hz). The components of $\tan \delta$ for a particular temperature and frequency may be determined from the data in Section III.

Information on the relative damping capacities of different kinds of viscoelastic materials is particularly applicable to problems of vibration isolation where damping efficiency at a particular frequency or frequency interval is desirable information.

III. MATERIAL PROPERTIES OF ELASTOMERS

A. Butadiene Rubber (BR)

General Information:

Polybutadiene is a homopolymer of butadiene. It can be prepared in either a solution or an emulsion polymerization system. Polybutadienes in commercial production are 1,4 polymers produced through solution polymerization using Ziegler-type catalysts to give a high content of cis-structure. Polybutadiene can be vulcanized with common curing agents. Thiazoles and sulfenamides are commonly used. The rate of cure of polybutadiene is similar to that of SBR.

Polybutadiene(cis) is often mixed with other elastomers. It is commonly used commercially in tire tread, hose, tubing, soles and equipment mounts, due to its abrasion resistance and high resilience.

Notable Characteristics:

Excellent resistance to low temperature brittleness. Good abrasion and flex resistance. Tensile strength is lower than that of natural rubber; can be improved through carbon black loading. Polybutadienes are more permeable to gases than SBR or natural rubber. Similar to SBR and natural rubber in resistance to oxidation and ozone. High volume resistivity. Fairly resistant to acids and alkalies.

Poor resistance to aliphatic and aromatic hydrocarbons and chlorinated solvents. Poor resistance to lubricating and hydraulic oils and fuels.

1. Physical Properties for Vulcanizate

100% Modulus (MPa)	2.93
Tensile Strength	11.6
Ultimate Elongation	260%
Shore A Hardness	63
Density (g/cm^3)	1.12
Low Temperature Stiffness ($^{\circ}$C)	-35

2. Recipe for Polybutadine

Component	Parts	Trade Name and Suggested Supplier
62% vinyl content polybutadiene	100	Firestone Tire & Rubber Co., Akron, O
FEF Carbon Black	55	- - -
Magnesium Oxide	3.7	Elastomag No. 100, Morton Chemical Co., Chicago, IL
Calcium Oxide	1.7	Hydrated Lime No. 43, Harwick Std. Chem. Co., Akron, O
Aromatic processing oil	5.0	Dutrex 726, Shell
Resin plasticizer	10.0	Piccoumaron XX100, Pa. Ind. Chem. Co., Pittsburgh, PA
Sulfur, rubber grade	5.0	- - -
Primary Accelerator	0.9	Santocure NS, Monsanto Chem. Co., Akron, O
Secondary Accelerator	0.2	Methyl Tuads,, R.T. Vanderbilt Co., Akron, O.

TOTAL   181.5

Cured for 30 minutes at 150°C (302°F) in press.

3. **Shear Modulus of Polybutadiene** (Ref.32)

POLYBUTADIENE

$$\log a_T = \frac{-37.5(T-10.00)}{382 + T}$$
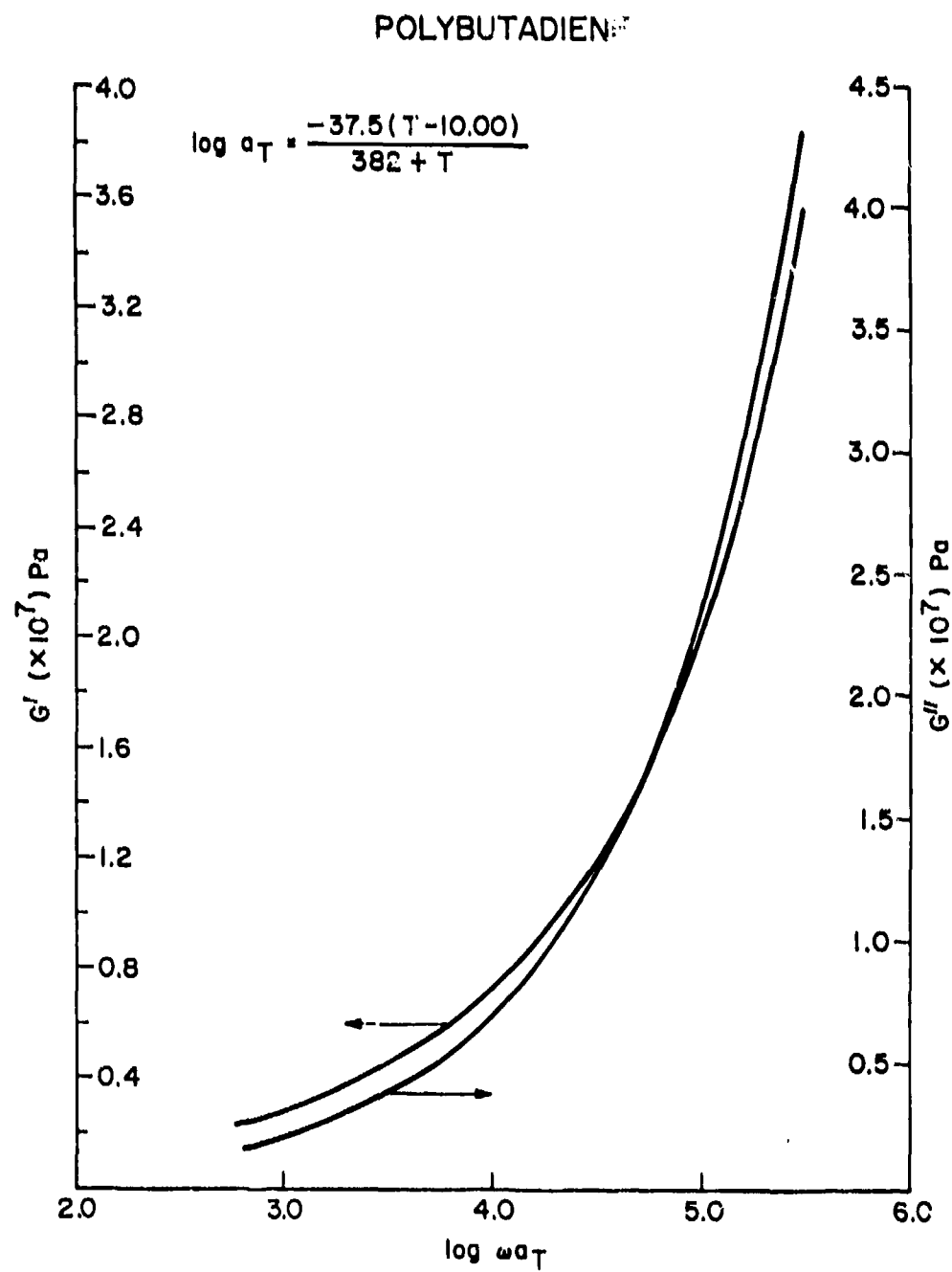
B. Butyl Rubbers

1. Butyl Rubber (IIR)

General Information:

Butyl rubber is a general purpose, non-oil resistant elastomer resulting from the copolymerization of isobutylene and isoprene. Many of the physical properties of butyl rubber are a function of the crosslink density, which is directly proportional to the isoprene content of the polymer. Proportions of isoprene may be varied from low, for good ozone, chemical, and flex resistance, to higher values for improved tensile and abrasion characteristics. Commonly used fillers and reinforcing agents include both carbon black and mineral fillers. Carbon blacks provide superior reinforcement compared to mineral fillers with smaller particle sizes providing higher tensile strengths and hardnesses.

Notable Characteristics:

Outstanding permeation resistance to both gases and water. Excellent dielectric and insulation resistance when talc filled. High damping and good abrasion resistance.

Resistant to ozone, acids, alcohols, esters, and ketones. Poor resistance to hydrocarbon oils and gasoline.

Properties	Hardness (Shore A)	
	40	80
Tensile Strength (MPa)	7.9-13.8	6.9-16.5
Ultimate Elongation (%)	680-840	190-620
300% Modulus (MPa)	0.6-4.0	3.9-14.3
Density (g/cm^3)	1.12-1.15	1.23-1.30
Low Temperature Stiffness (°C)	-23 to -29	-18 to -29
Coefficient of Thermal Expansion (cm/cm/°C)	9.0×10^{-4}	6.8×10^{-4}
Volume Resistivity (ohm-cm)	10^{17}	10^{17}
Dielectric Strength (Kvolts/cm)	∿236	∿236
Dielectric Constant	2-5	2-5
Water Absorption 57° -19 days (mg/cm^2)	4.3	1.6
Water Permeability 38°C (10^{-10}gH$_2$Ocm/cm^2/cm-hr-torr)		44

a. *Compounding Recipe*

        The gum vulcanizate of the accompanying figure was prepared according to the following recipe:

Ingredient	Parts
Butyl	100
Zinc Oxide	5
Tuads	1
Sulfur	1.5

    The density of the cured material, along with cure time and temperature, was not given in Ref. 31.

b. *Longitudinal Modulus of Butyl Rubber*

Re: $T_R = 10°C$

$$\log a_T = \frac{-2.40(T-10.00)}{T+64.20}$$
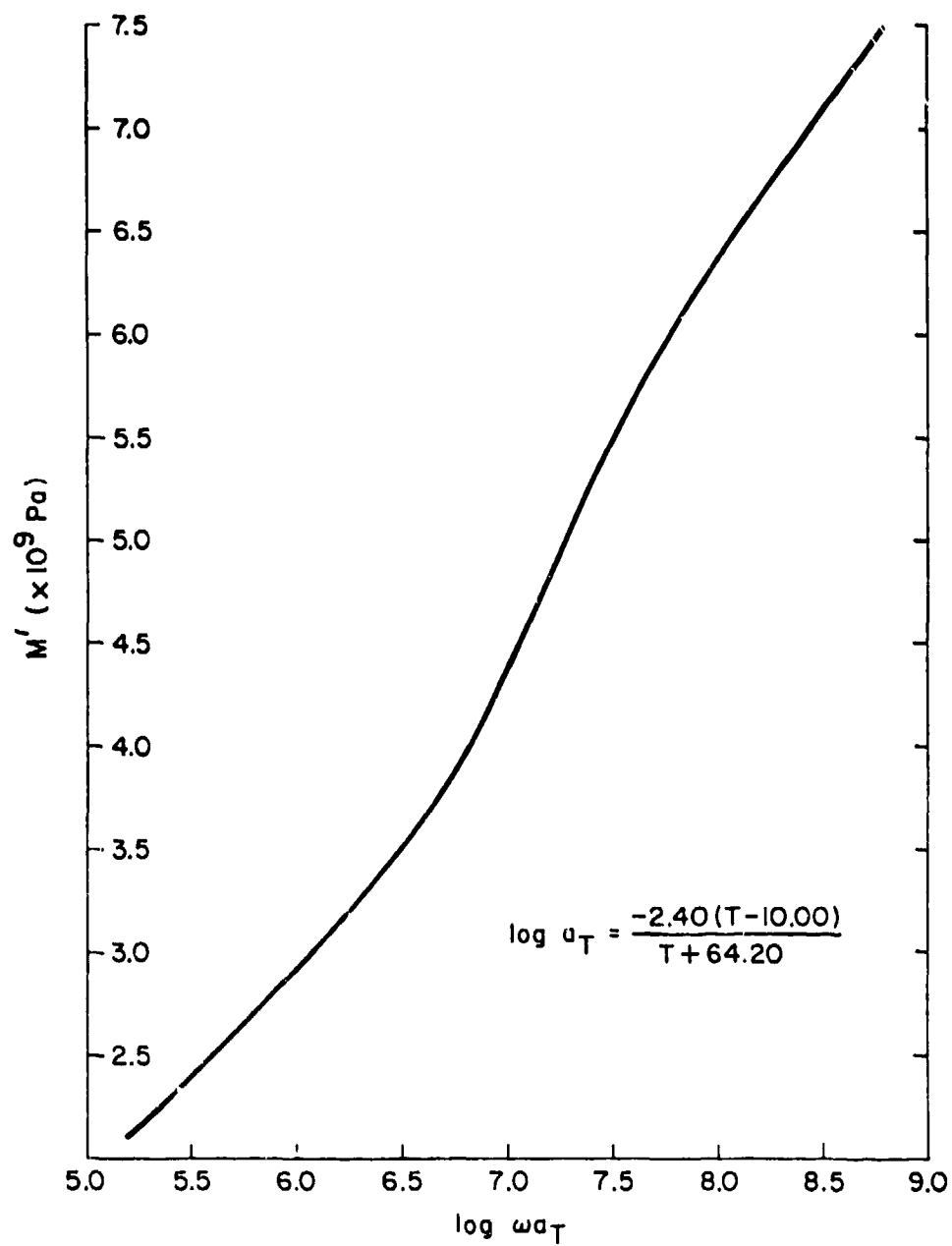
(Reduced curves taken from data in Ref. 31.)

2. Butyl 70821 (USRD Use)

    a. *Compounding Recipe*

Ingredient	Parts
Enjay Butyl 217	100.0
Stearic Acid	0.5
Culcived Clay	85.0
Whiting	40.0
Zinc Oxide	5.0
Polyethylene	6.0
Lurrafin Wax	4.0
EPC Black	10.0
Dibenzo GMF	6.0
Red lead	9.0
Sulfur	0.8
Polyac	0.15

Cure: 60 minutes at 153°C (307°F) in press.

Vulcanizate density: 1.48 g/cm^3 at 25°C

    b. *Physical Static Properties*

Tensile Strength (MPa)	4.8
Elongation (%)	500
300% Modulus (MPa)	3.1
Resistivity (ohm-cm)	4.3×10^{14}
Power Factor (%)	0.37
Dielectric Constant	3.59

c. *Shear Modulus of Butyl 70821*

(Ref. 32)

$$\log a_T = \frac{-4.78\,(T-10.00)}{71.1 + T}$$
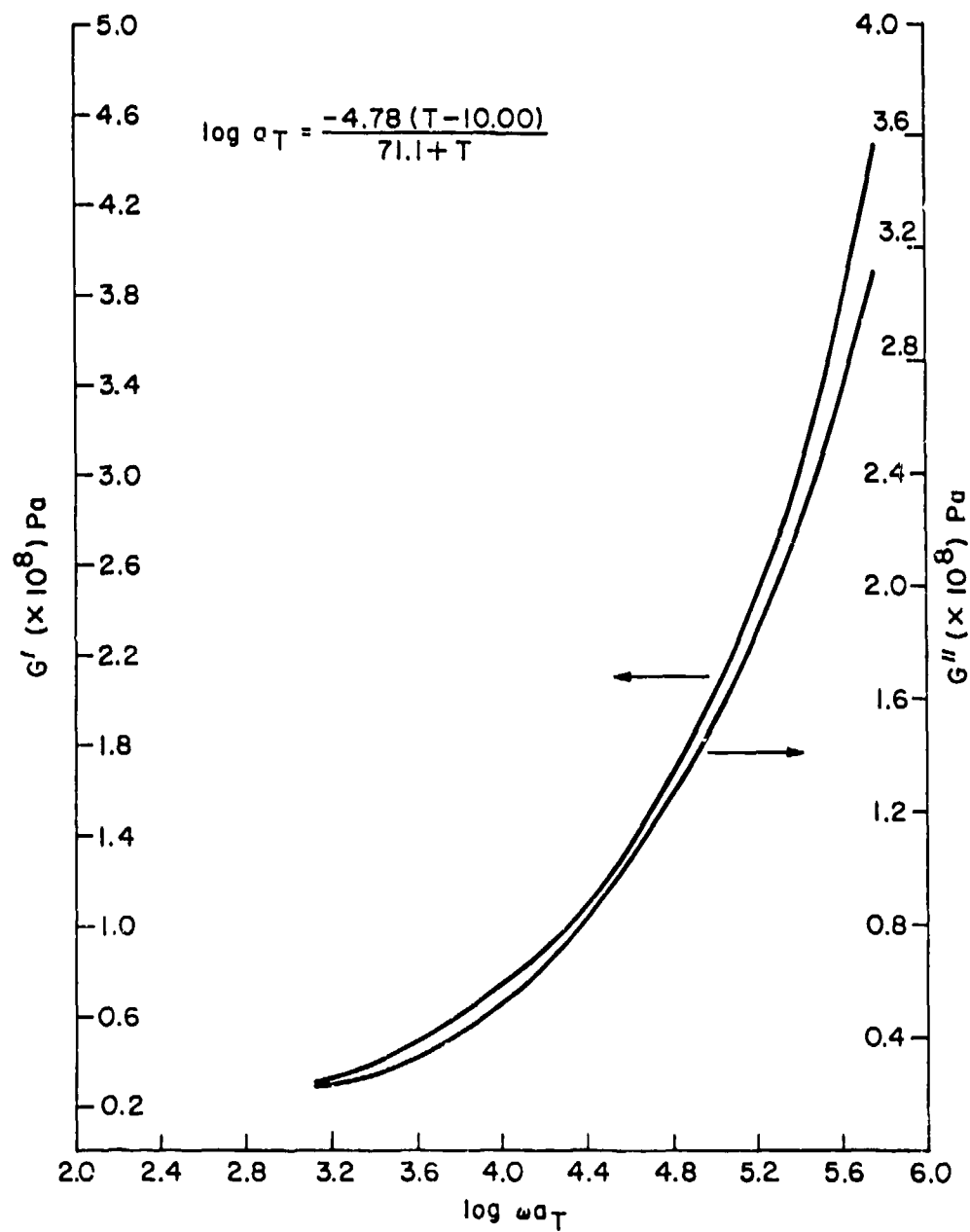
3. Butyl B252 (USRD Use)

   a. *Compounding Recipe and Physical Static Properties*

Ingredient	Parts
Enjay Butyl 150 (replacement Exxon 268)	100
Pelletex (SRF Black)	50
Zinc Oxide (Kadox 72)	5
Red lead	10
Circo Light Process, Oil	5
Dibenzo GMF	3
AA-1177-20 Wax	6

- -

Cure: 40 minutes at 153°C (307°F) in press

Vulcanizate density: 1.16 g/cm^3 at 25°C

Properties:

Tensile Strength (MPa)	9.0
Ultimate Elongation (%)	575
300% Modulus (MPa)	5.5
Hardness (Shore A)	50-60
Water Permeability (20°C) (10^{-10}gH$_2$0cm/cm^2-hr-torr)	12

Note: The electrical properties of this compound may
make it unsuitable for use as a primary insulator.

b. Bulk Modulus of Butyl B252 (Ref. 33)

STATIC PRESSURE; 5°, 25°, 40°C Re 0.69 MPa
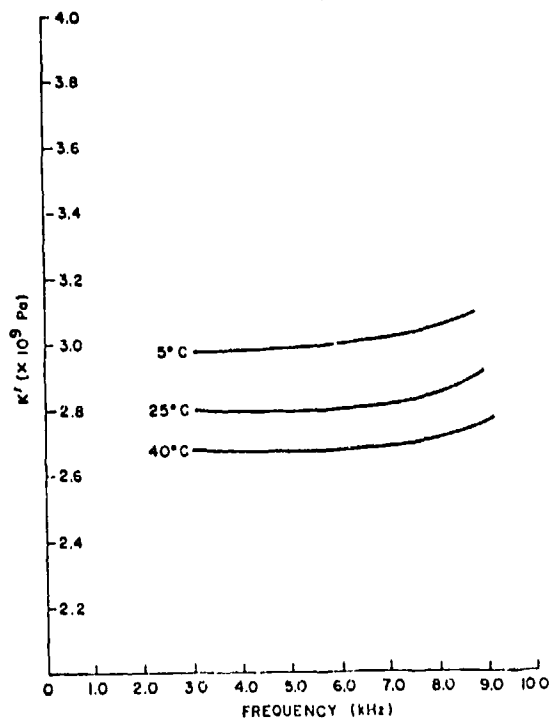
STATIC PRESSURE; 5°, 25°, 40°C Re 3.45 MPa
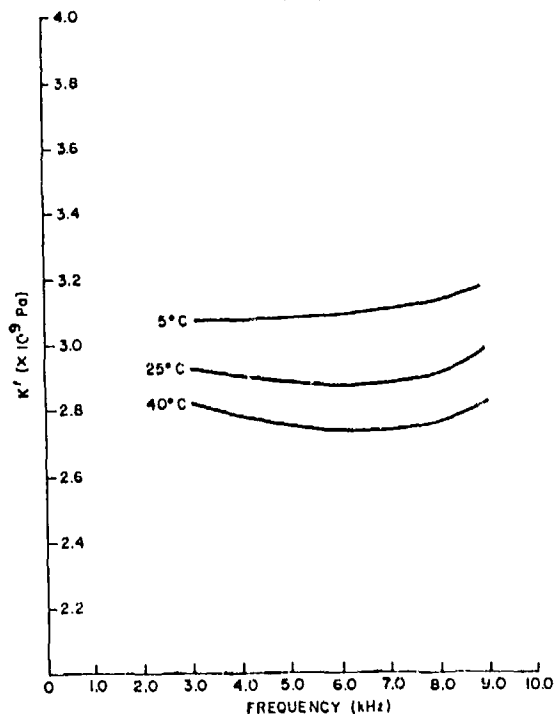
STATIC PRESSURE; 5°, 25°, 40°C Re 6.90 MPa
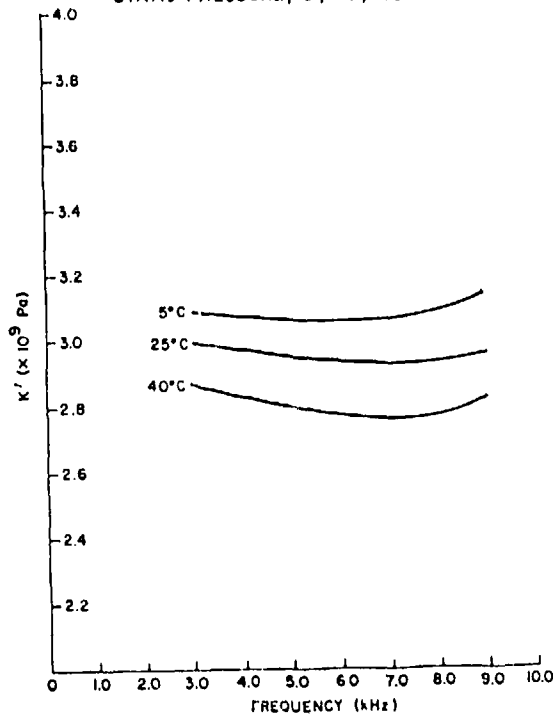
STATIC PRESSURE; 5°, 25°, 40°C Re 13.79 MPa
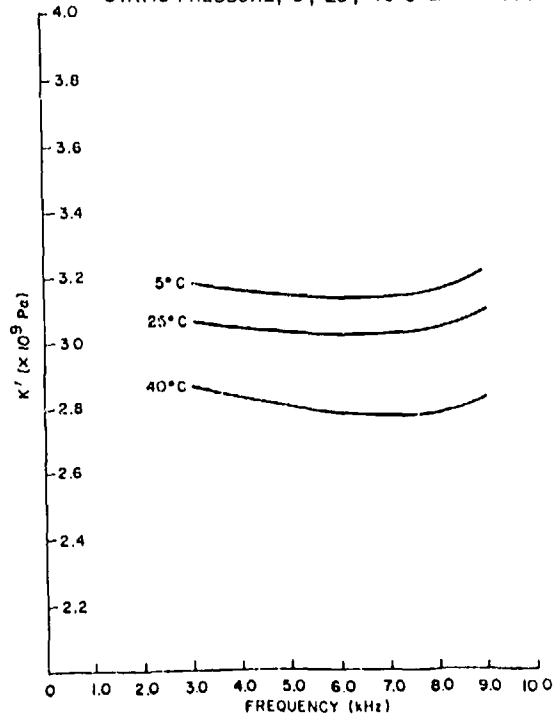
c. *Shear Modulus of Butyl B252*

(Ref. 32)

$$\log a_T = \frac{-17.1\,(T-10.00)}{240+T}$$
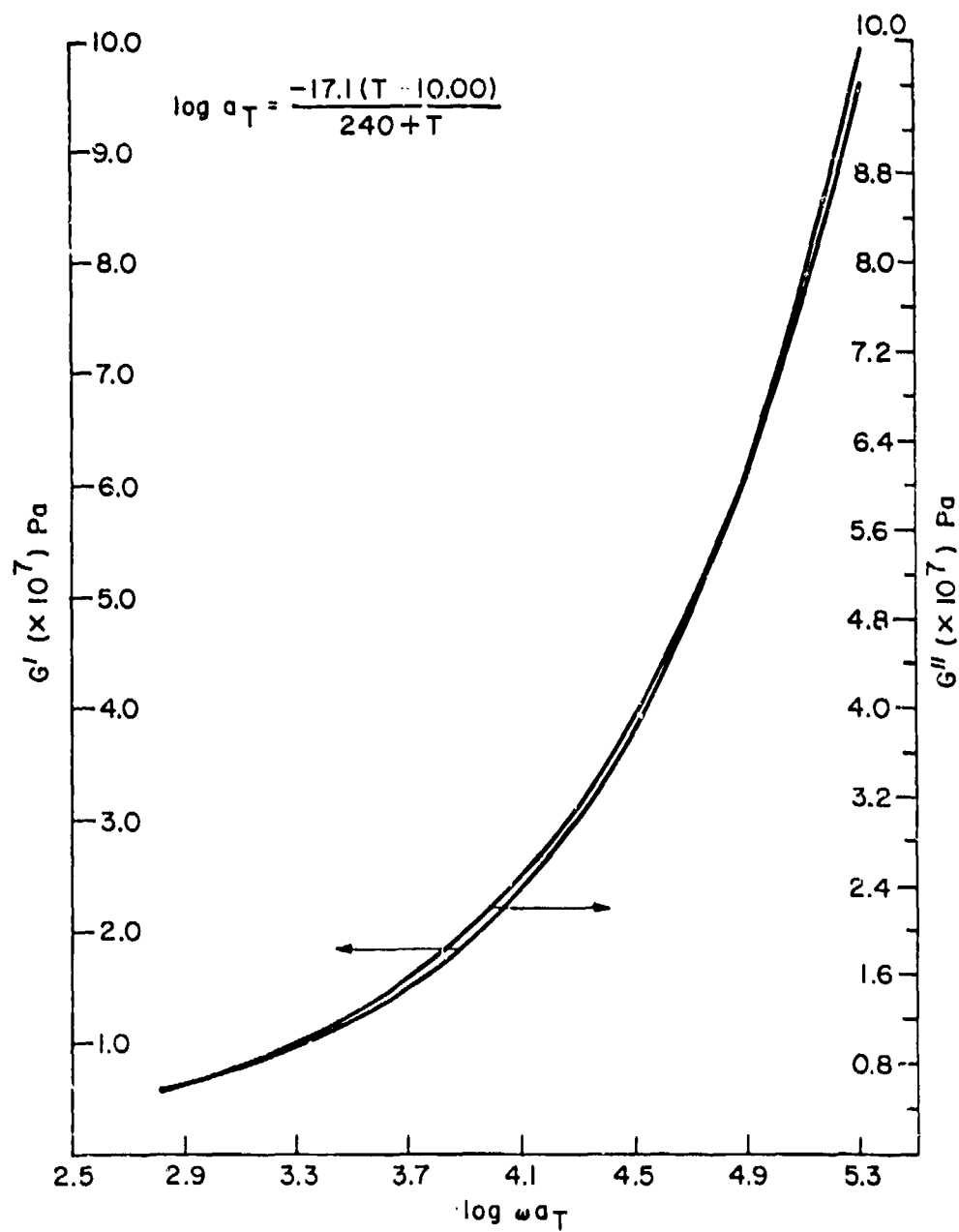
d. *Sound Speed in B252 as a Function of Hydrostatic Pressure*
(Ref. 33)
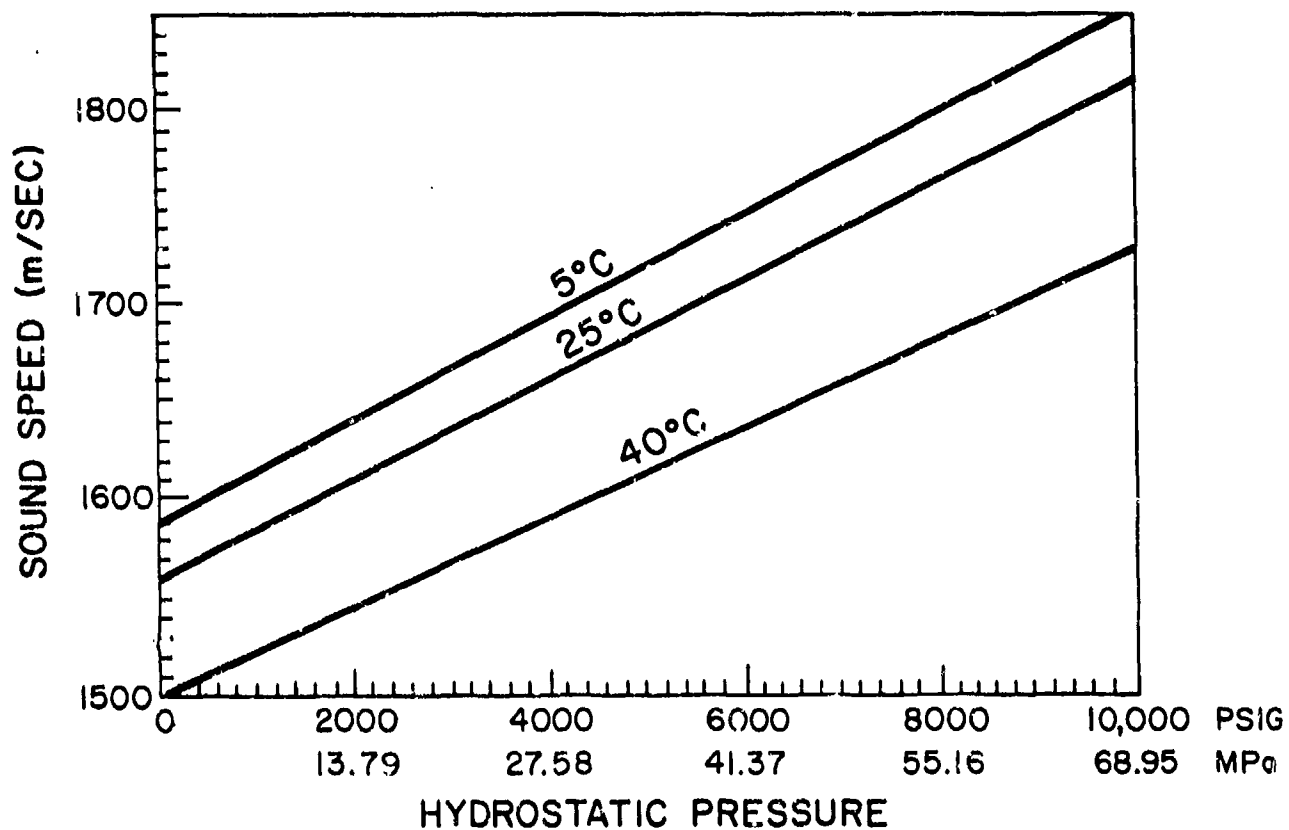
4. Chlorobutyl Rubber

a. *General Information and Characteristics*

General Information:

Chlorobutyl rubbers may be vulcanized with a wider variety of curing systems than butyl rubbers. This permits an expanded range of physical properties compared to the parent compounds. Chlorobutyls also have faster curing rates and superior heat, ozone, and chemical resistance than unmodified butyls.

Notable Characteristics:

Chlorobutyl rubbers adhere readily to metals and other elastomers. They form homogeneous blends with nitrile and neoprene rubbers. High tensile and tear strengths are characteristic of carbon black reinforced chlorobutyl vulcanizates.

b. *Representative Physical Properties*

	40 Durometer	60 Durometer
Tensile Strength (MPa)	5.9-10.0	12.4-17.9
Ultimate Elongation (%)	870-895	480-715
300% Modulus (MPa)	1.7-1.9	6.0-9.0
Density (g/cm^3)	0.96	1.01
Volume Resistivity (ohm-cm)	$\sim 10^{14}$	$\sim 10^{14}$
Water Permeability (38°C) $10-10_g H_2 O cm/cm^2$-hr-torr		49

5. Chlorobutyl H862A (USRD Use)

a. *Compounding Recipe and Physical Static Properties*

Ingredient	Parts
Chlorobutyl HT-1066	100
Sterling V Black	50
Red lead	10
Stearic Acid	1
AC Polyethylene 617	3
Diphenylguanidine	2
Maglite M (MgO)	1
Zinc Oxide	5
NA-22 (ethylene thiourea)	1.5

- -

Cure: 60 minutes at 154.5°C (310°F) in press
Vulcanizate density: 1.19 g/cm^3 at 25°C

Properties:

Tensile Strength (MPa)	11.2
Ultimate Elongation (%)	375
300% Modulus (MPa)	10.3
Hardness (Shore A)	55-60
Water Permeability (20°C) $(10^{-10}$g H$_2$0cm/cm^2-hr-torr)	8

Note: The electrical properties of this compound make it
unsuitable for use as a primary insulator.

44

b. *Sound Speed in Chlorobutyl H682A as a Function of Hydrostatic Pressure* (Ref. 33)
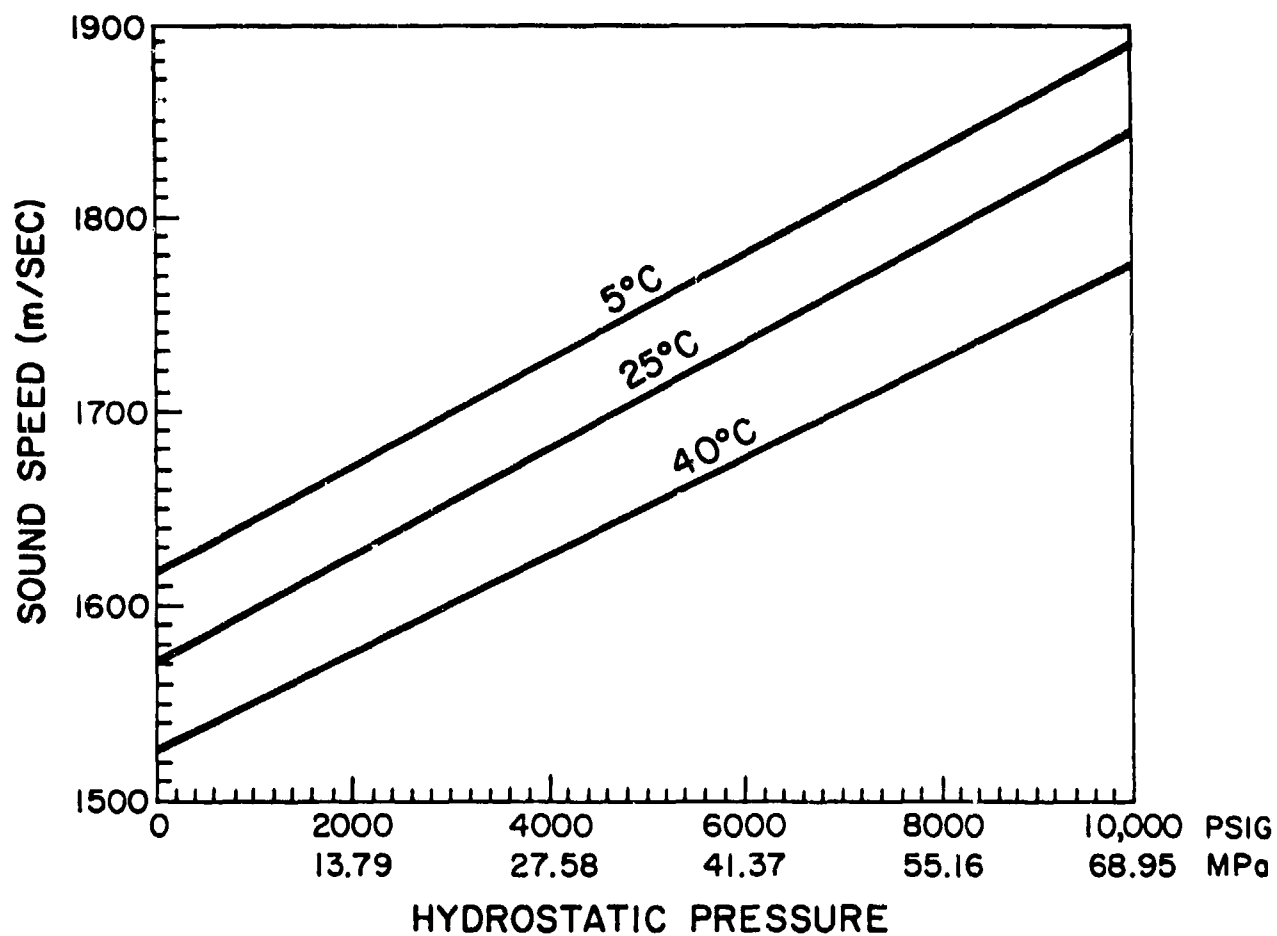
C. Chlorosulfonated Polyethylene (Hypalcn-20)

General Information:

Chlorosulfonated polyethylene is obtained by treatment of low molecular weight polyethylene with chlorine and sulfur dioxide. Several grades are available differing in their respective chlorine and sulfur contents. The modulus of the cured rubber is prop~tional to the sulfur content of the prevulcanized material. Cure is effected by heating with metal oxides in the presence of an organic acid. Red lead improves water resistance. Cured Hypalon exhibits higher strength properties than Neoprene and very good weatherability.

Hypalon has poor resistance to gasoline, aromatic solvents, and chlorinated hydrocarbons.

Notable Characteristics:

Superior ozone resistance, better than any other elastomer. Excellent resistance to acids and oxidizing agents; high modulus and stiffness.

1. Physical Static Properties

Tensile Strength (MPa)	16.6-26.2
Ultimate Elongation (%)	200-560
200% Modulus (MPa)	12.4-23.4
Density (g/cm^3)	1.12-1.28
Low Temperature Stiffness (°C)	-40
Coefficient of Volume Expansivity (cm^3/g·°C)	6.8-7.3
Volume Resistivity (ohm-cm)	1×10^{13}
Dielectric Strength (Kvolts/cm)	157-295
Hardness (Shore A)	60-95
Water Absorption	

2. Compounding Recipe

Component	Parts
Hypalon 20 (27.77% Cl; 1.24% S)	100
Hydrogenated wood rosin	2.5
Litharge (PbO)	40
Dipentamethylene thiuram tetrasulphide	0.75
MDTS (Benzthiazyl disulfide)	0.50

- -

Cured stock density (25°C)	1.13 g/cm^3

Samples molded at 93°C (200°F) for 12 minutes

3. Shear Modulus for Hypalon-20 (Ref. 34)

$$T_R = 12.7°C$$

$$\log a_T = \frac{-7.20\,(T - 12.7)}{T + 55.0}$$
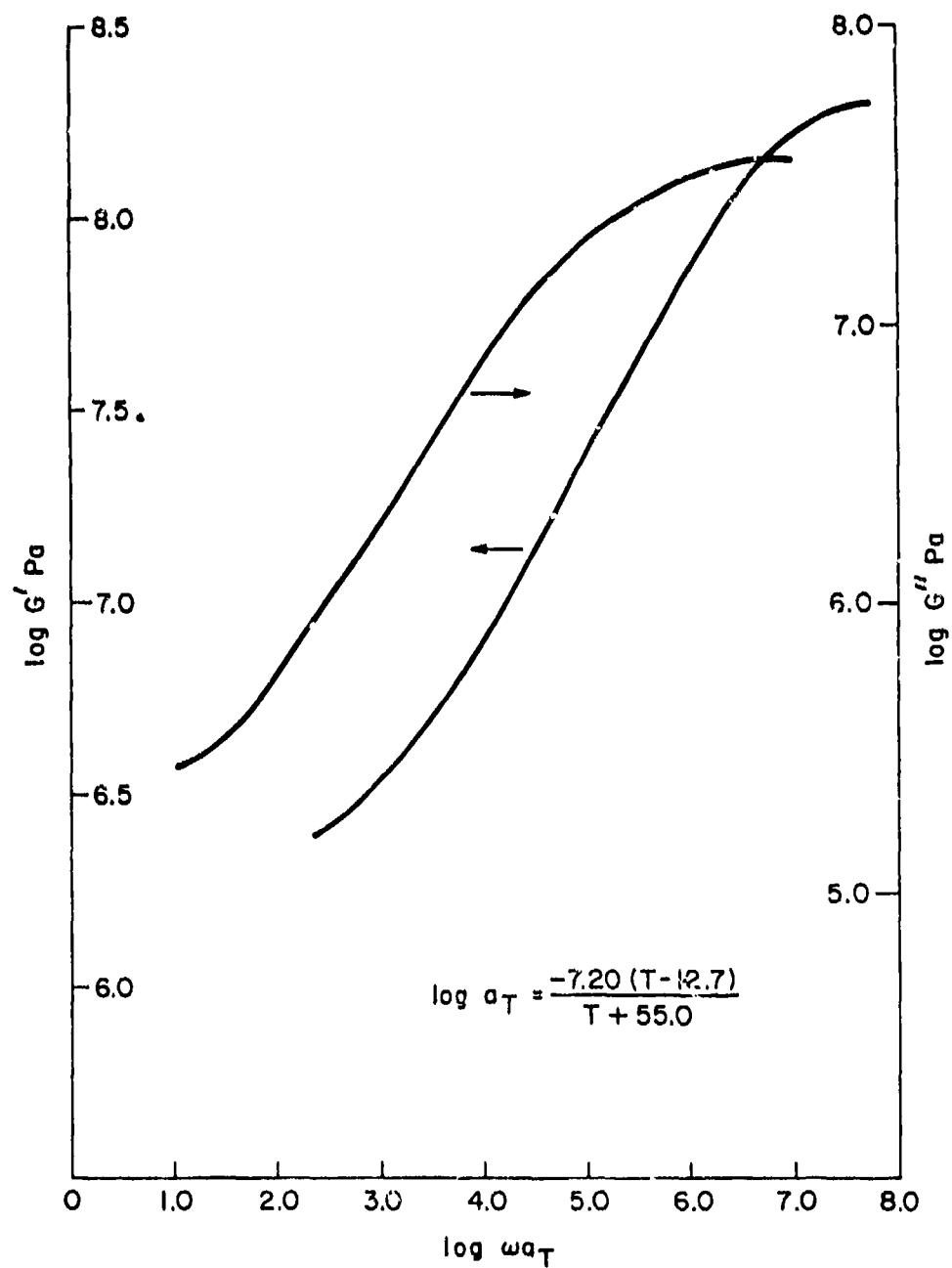
D. Ethylene Propylene Diene Rubber (EPDM)

1. General Information and Characteristics

General Information:

Ethylene-propylene-diene is a terpolymer based upon ethylene, propylene, and a controlled amount of a nonconjugated diene. Dicyclopentadiene, ethylidene norbornene, and 1,4 hexadiene are normally selected as the nonconjugated diene component. The unsaturation remaining after the initial synthesis is pendant to the main chain and permits classical sulfur vulcanization. EPDM elastomers can be compounded in a variety of formulations to yield compounds with high and low hysteresis for energy absorption and resilience, respectively.

Notable Characteristics:

Outstanding resistance to ozone and weathering. Appropriate compounding gives good high temperature performance. Good low temperature flexibility. Good resistance to ozone and weathering make EPDM useful for electrical wire covering. Tear resistance is similar to SBR, but not as good as natural rubber. Particularly resistant to superheated steam and hot water. Resistant to many acids and alkalies, ketones, and alcohols.

Poor oil and hydrocarbon resistance. Unsuitable for contact with hydrocarbon solvents and oils or chlorinated solvents.

2. Compounding Recipe for Royalene 400 (EPDM)

Component	Parts	Trade Name and Suggested Supplier
EPDM	120.0	Royalene 400 Uniroyal Chemical
MB-X352	47.1	See below
Zinc Oxide	10.0	Various
Red Lead	10.0	Various
SRF Black	10.0	Various
Aluminum Silicate	200.0	Burgess KE Clay, Burgess Pigment
Paraffinic Oil	30.0	Various
Dicumyl Peroxide	3.9	Di Cup R, Hercules Chemical
p,p'-Dibenzoylquinone dioxime	1.0	Dibenzo GMF Uniroyal Chemical
Total	432.0	

MB-X352 (For use in Royalene 400)

Ingredient	Parts
Royalene 400	20.0
Polyethylene	20.0
Polymerized trimethyldihydroquinoline	1.0
Burgess KE Clay	5.0
Dicumyl Peroxide (Di Cup R)	1.1
Total	47.1

Cure: 25 min. at 320°F/160°C in press

Density: 1.38 g/cm^3

3. Shear Modulus of Royalene 400-EPDM (Ref. 32)
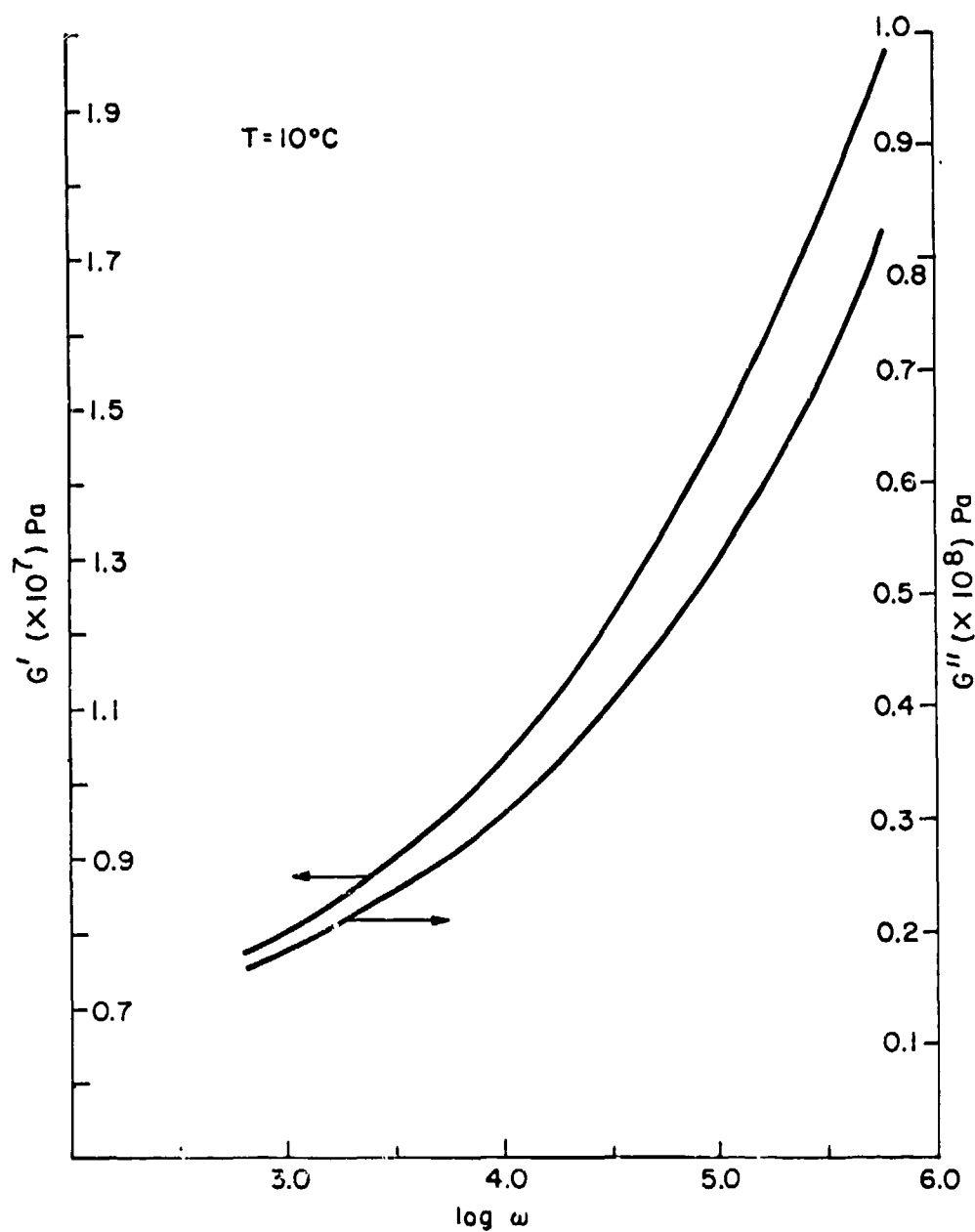
E. Fluorocarbon Rubbers (CFM)

1. General Information and Characteristics

General Information:

Fluorocarbon elastomers are synthetic polymers which contain varying proportions of fluorine. This imparts a high degree of resistance to a variety of hot solvents and oils while retaining relatively good room temperature strength characteristics after prolonged heat aging. Chemically, the most important fluorocarbon polymer is a copolymer of vinylidene fluoride and chlorotrifluoro ethylene. It is marketed under the trade name of Viton by Dupont and Fluorel by 3M Company.

Vulcanization is usually initiated by a combined system of peroxide and metal oxides, although amines and iso cyanates are sometimes used. The cure is normally done in two parts, with an oven post-cure of 10 to 24 hours at 204°C following the initial press cure.

Notable Characteristics:

Good resistance to high temperatures. Good resistance to hot oils, lubricants, acids. Low swelling in aliphatic and aromatic oils and chemicals. Excellent resistance to sunlight, weathering, and ozone. Low temperature properties are only moderately good. Low compression set.

Electrical properties are best suited for low voltage, low frequency applications where chemical and thermal stability are required.

Poor resistance to organic acids, ketones, aldehydes, and highly polar fluids.

2. Physical Static Properties

Tensile Strength (MPa)	16.9
100% Modulus (MPa)	7.2
Ultimate Elongation	160%
Hardness(Shore A)	75
Density (g/cm^3)	1.79
Low Temperature Stiffness ($^{\circ}$C)	-35 to -45
Water Permeability (20°C) $(10^{-10}gH_2Ocm/cm^2$-hr-torr)	520

3. <u>Viton A</u>

   a. *Compounding Recipe*

Ingredients	Parts
Viton A	100
MT Carbon Black	18
Magnesium Oxide	15
Ethylenediamine Carbamate . . .	1

Cured at 150°C for 1 hour and post-cured in open air at 200°C for 24 hours.

Density – 1.79 g/cm^3

b. *Shear Modulus of Viton A*   (Ref. 35)

$$\log a_T = \frac{-12.5\,(T-10.00)}{113+T}$$
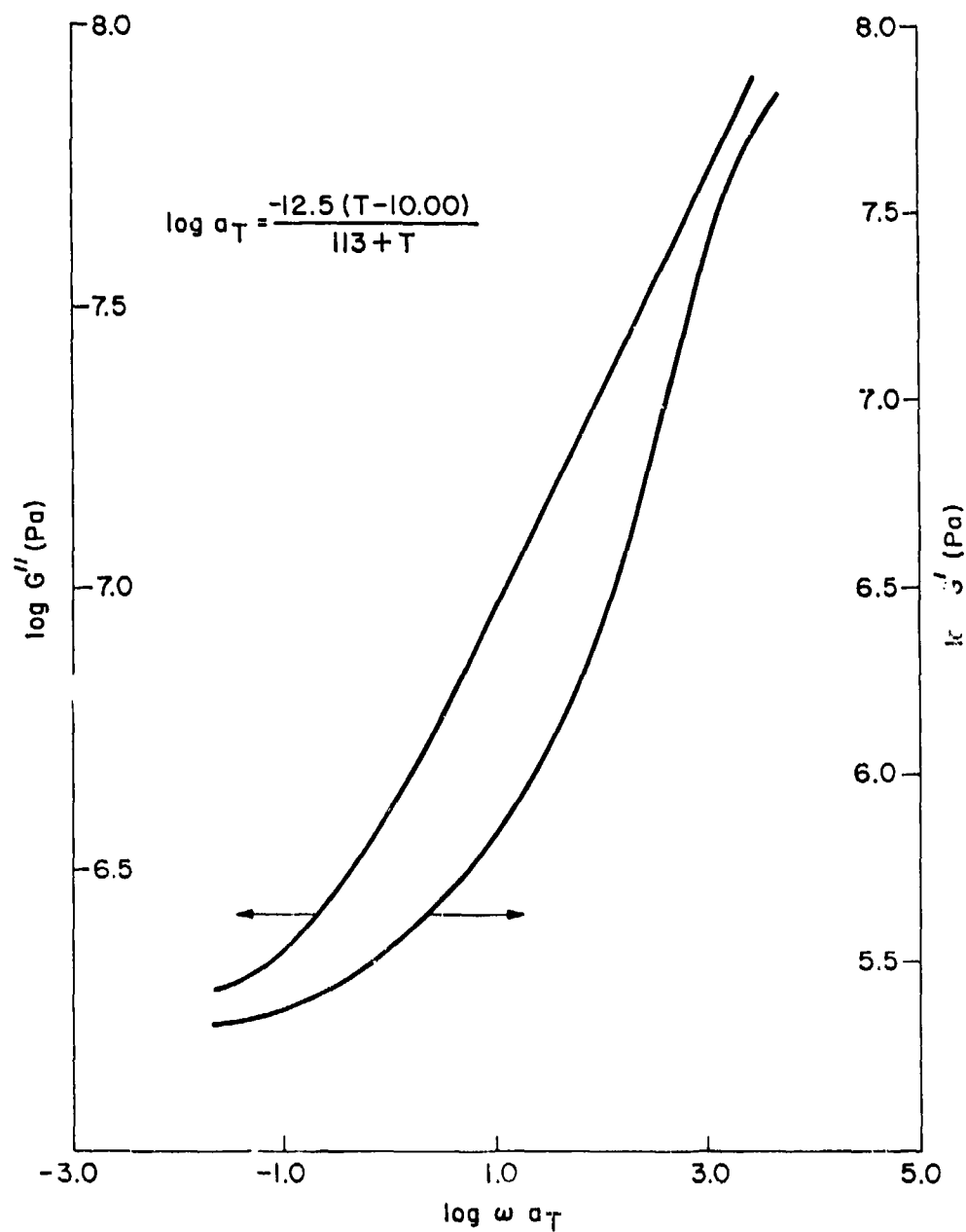
4. <u>Viton B-50</u>

    a. *Compounding Recipe*

<u>Ingredients</u>   <u>Parts</u>

Viton B-50 100

MT Carbon Black 20

Magnesium Oxide
(Maglite Y) 15

N,N' - Dicinnamylidene
1,6 - hexane diamine
(Diak No. 3) 3

Cured for 15 minutes at 169°C in press. Post-cured in oven for 24 hours at 204°C.

Density - 1.99 g/cm^3

    b. *Physical Static Properties*

Tensile Strength (MPa) 15.9

100% Modulus (MPa) 3.8

Ultimate Elongation (%) 250.0

Hardness (Shore A) 68.0

c. *Shear Modulus of Viton B-50*   (Ref. 32)

56
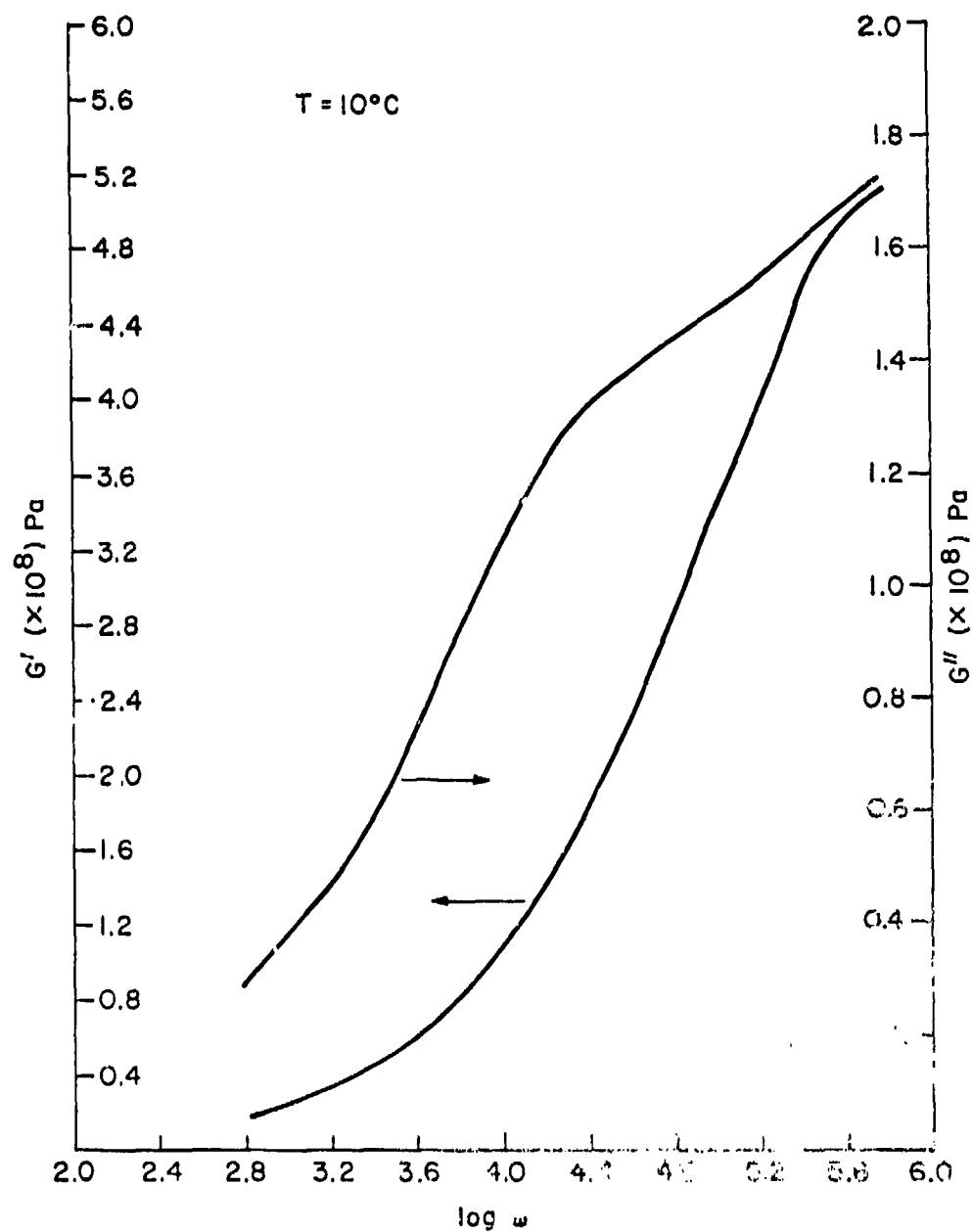
5. Viton B-910

   a. *Compounding Recipe*

Ingredients	Parts
Viton	100
MT Carbon Black	30
Magnesium Oxide (Maglite D)	3
Calcium Hydroxide	3

   Cured for 5 minutes at 177°C in press. Post-cured for 24 hours at 204°C.

   Density – 1.84 g/cm^3

   b.. *Physical Static Properties*

Tensile Strength (MPa)	16.2
100% Modulus (MPa)	6.2
Ultimate Elongation	220%
Hardness (Shore A)	78.0

c. *Shear Modulus of Viton B-910* (Ref. 32)

$$\log a_T = \frac{-5.17(T-10.00)}{40.5+T}$$
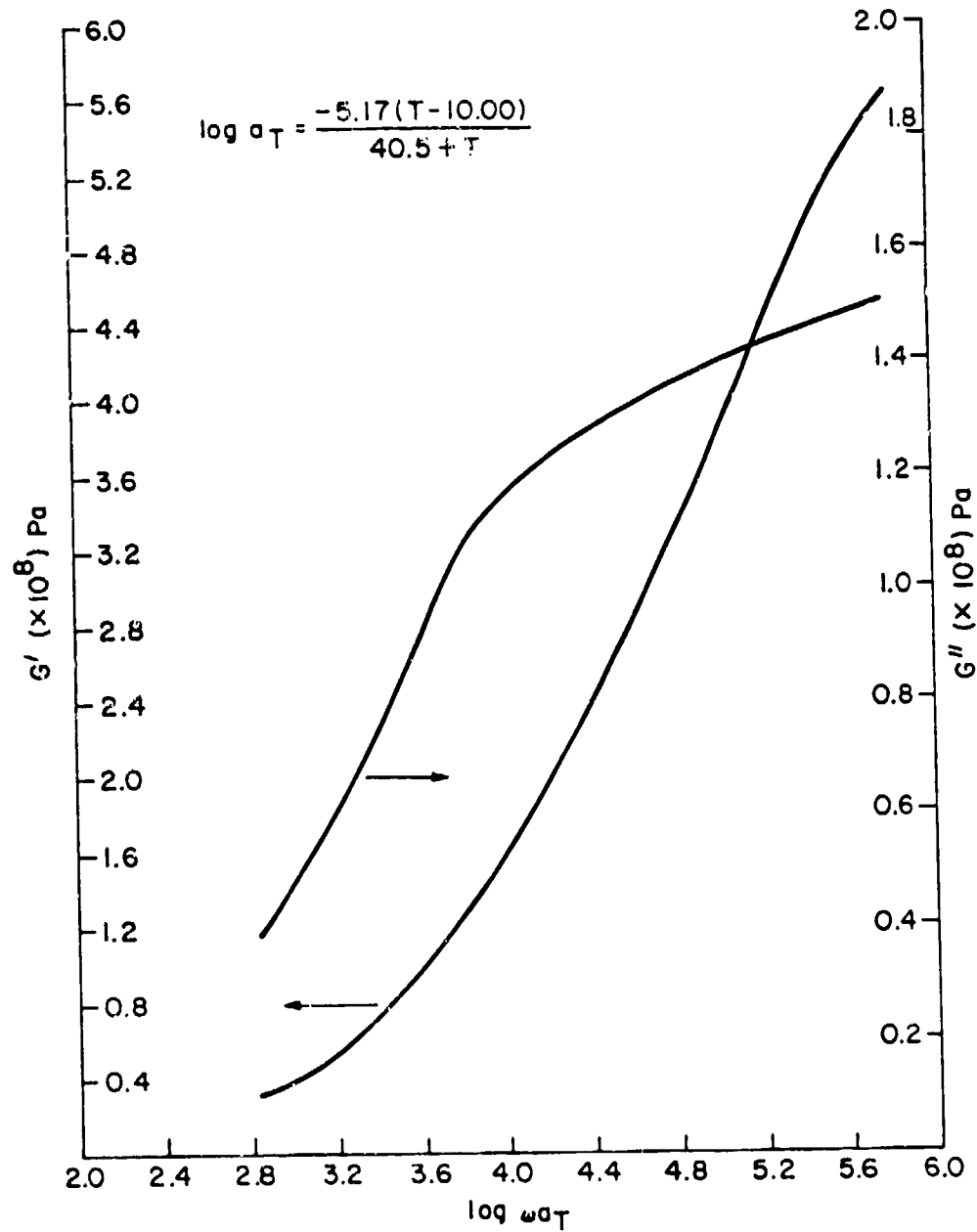
F. Polyisobutylene (PIB)

   1. <u>General Information and Characteristics</u>

General Information: Polyisobutylenes find application primarily in adhesive formulations and as flexibilizers for polyethylene resins. Although polyisobutylene is extremely difficult to vulcanize because of its tendency to undergo chain scission, it has been compounded with graphite and sawdust and utilized as an anechoic (sound ablative) coating.

Notable Characteristics: Exceptional oxidation and water resistance. Polyisobutylene resins are soluble in hydrocarbons and chlorinated hydrocarbons and are subject to creep or cold flow.

No nondynamic Physical Properties were available.

2. Bulk Modulus of NBS Polyisobutylene (IM) (Ref. 29)

$$T_R = 10°C$$

$$\log a_T = \frac{-6.36(T-25)}{112.2+T}$$
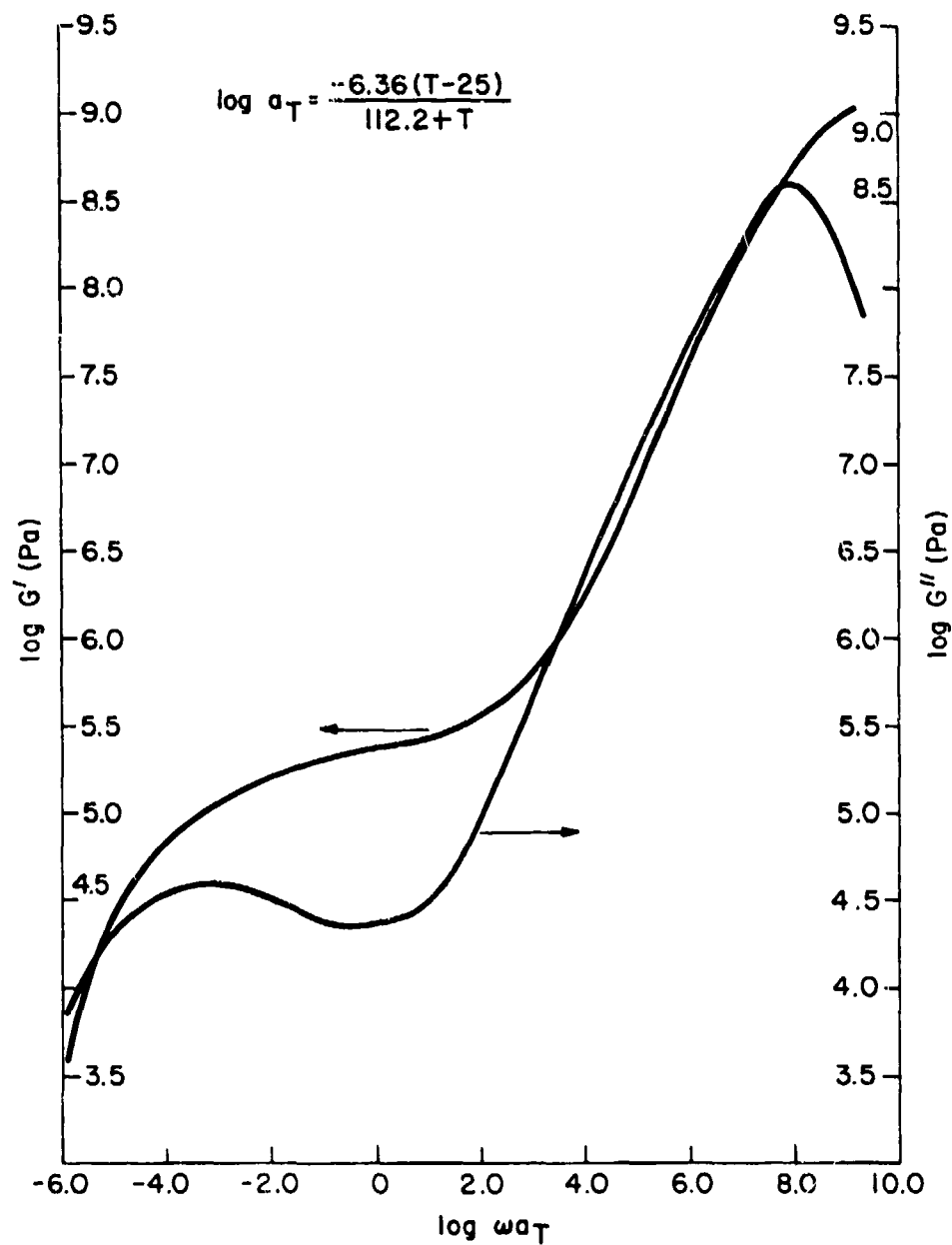
3. <u>Shear Modulus of NBS Polyisobutylene (IM)</u> (Ref. 29)

$$T_R = 10°C$$

$$\log a_T = \frac{-6.36\,(T-25)}{112.2 + T}$$
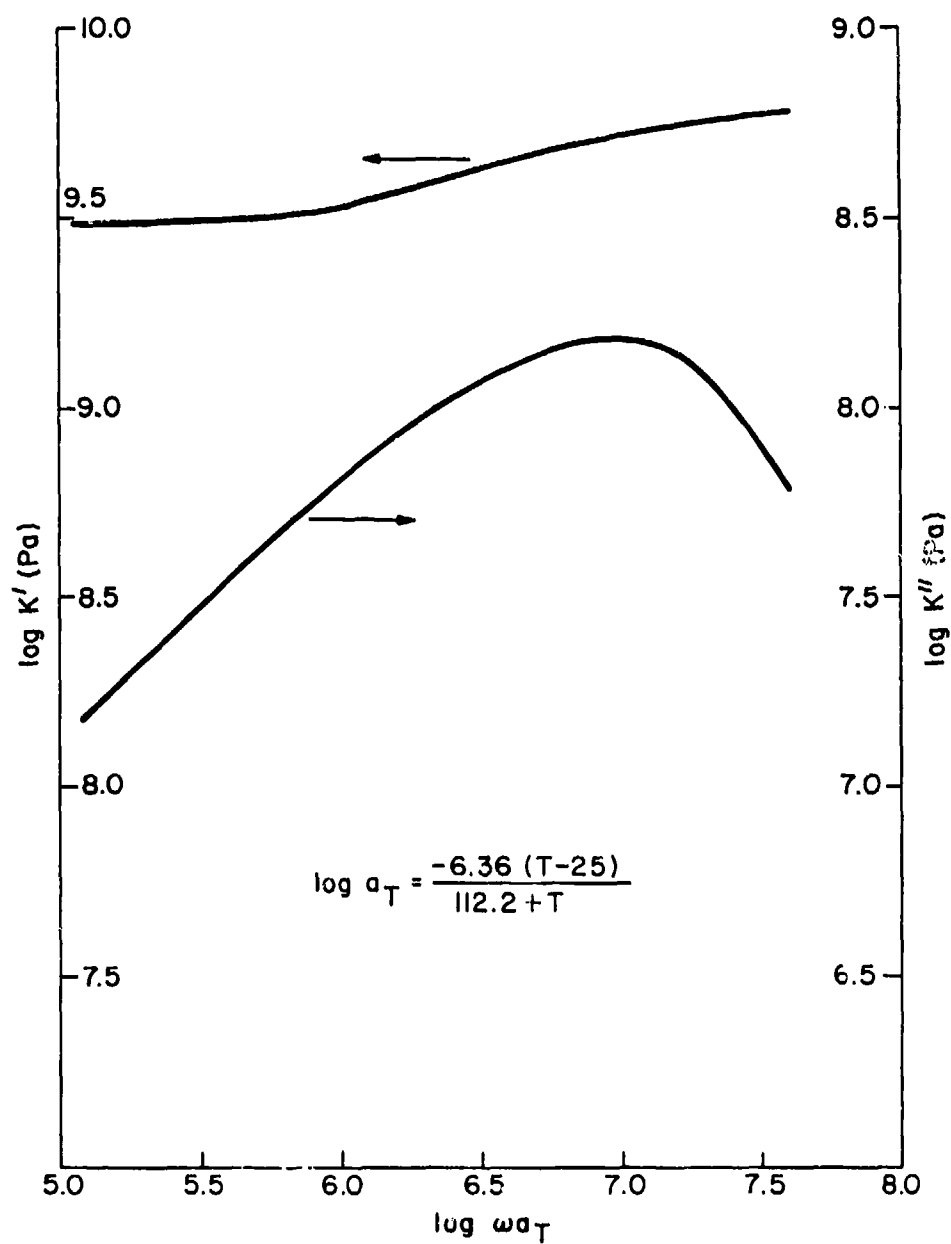
G. Natural Rubber (Unfilled and Filled)

1. General Information and Characteristics

General Information:

Natural rubber is the coagulated sap latex of the tree Hevea brasiliensis. It must be blended with inorganic or carbon black reinforcing agents and sulfur, then vulcanized to exhibit maximum physical properties. Physical properties depend upon the extent of vulcanization which in turn depends upon the amount of sulfur contained in the final product.

Vulcanizates of natural rubber should not be used in the presence of hydrocarbon or chlorinated solvents, fuels, or metallic alloys containing manganese or copper. They also have poor oxidation (ozone) and weather resistance.

Notable Characteristics:

Superior tensile strength and elongation, abrasion resistance, resiliency, electrical resistance, and low temperature properties, when compared to most synthetic rubbers.

2. Physical Static Properties

	Unfilled Vulcanizate	25% Carbon black 10% Plasticizer
Tensile Strength (MPa)	20.7 – 27.6	20.7 – 27.6
Ultimate Elongation (%)	675 – 850	550 – 650
300% Modulus (MPa)	1.0 – 2.4	4.8 – 9.0
Density (g/cm^3)	0.96	1.12 – 1.20
Low Temperature Stiffness (°C)	–34 to –56	–34 to –51
Linear Coefficient of Thermal Expansion (cm/cm/°C)	4.5×10^{-4}	3.1×10^{-4}
Volume Resistivity (ohm–cm)	10^{15}	10^{14}
Dielectric Strength (kV/cm)	197 – 295	197 – 295
Dielectric Constant	2.7	2.9
Hardness (Shore A)	40	60
Water Permeability (10^{-10} gH_2O cm/cm^2–hr–torr)	– –	529

3. <u>Shear Modulus of Natural Rubber (Unfilled)</u>   (Ref. 34)

$$T_R = 20°C$$

$$\log a_T = \frac{-6.62\,(T-20.0)}{T+124.28}$$
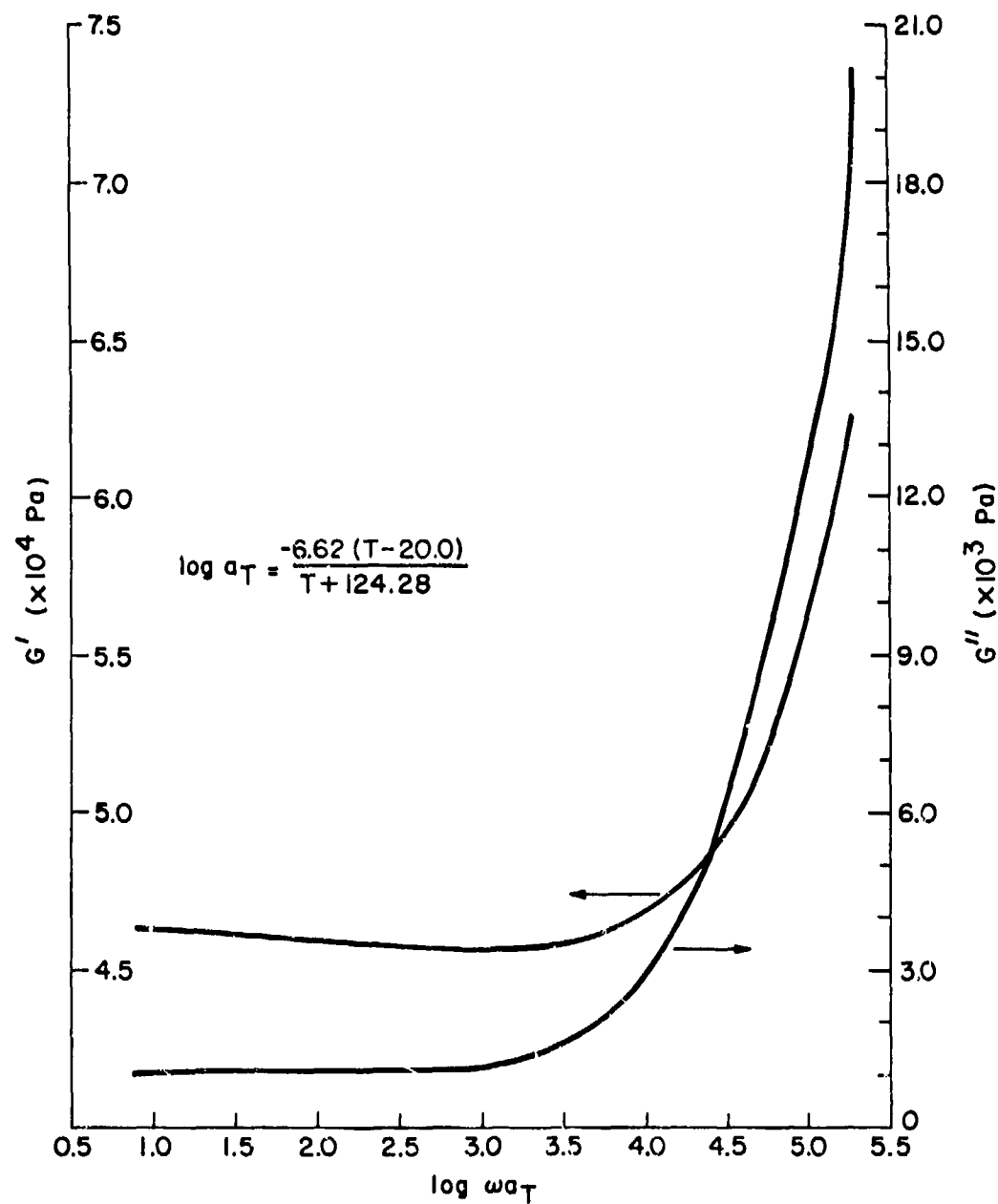
4. Shear Modulus of Natural Rubber Filled with 50 phr
HAF Carbon Black   (Ref. 34)

$T_R = 20°C$

$$\log a_T = \frac{-5.51(T-20.0)}{T + 96.88}$$
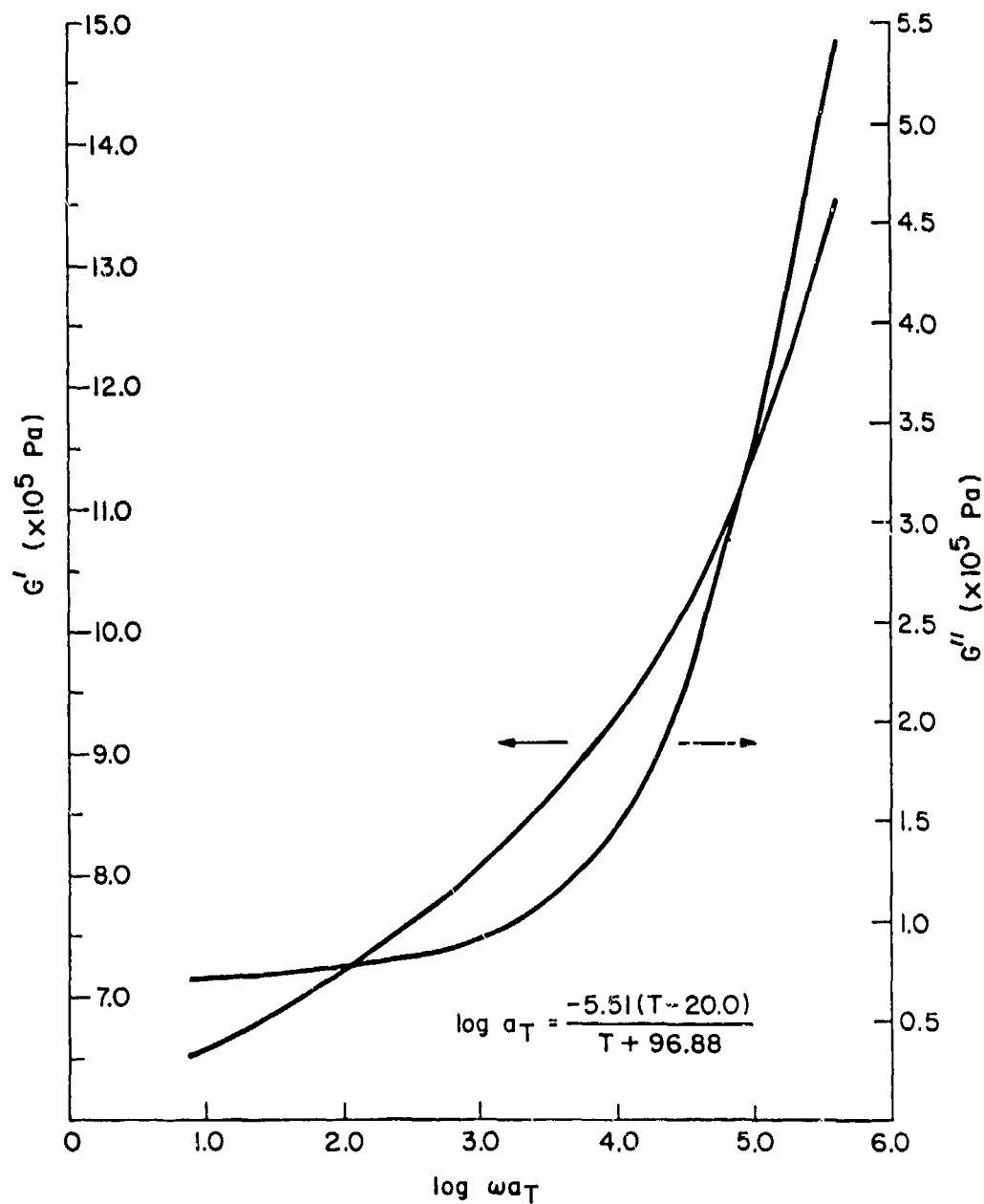
5. Components Used in Natural Rubber Formulations

Unads -- Tetramethyl thiuram monosulfide -- R. T. Vanderbilt, New York, NY.

SMR-5 -- Natural Rubber Formulation - Standard Malaysian Rubber Bureau,
1925 K St. N.W., Washington, D. C. 20006 - (202)452-0544

Protox 166 -- Zinc Oxide and Propionic Acid -- New Jersey Zinc.

Altax -- Benzothiazyl disulfide -- R. T. Vanderbilt, New York, NY.

Thermax(N-990) -- ASTM Carbon Black N-990 -- Various Suppliers.

Circosol 2XH -- ASTM oil #103 -- Sun Oil

Ingredients	334-289	334-290	334-291
SMR-5	100	100	100
Stearic Acid	1	1	1
Octamine	2	2	2
Circo LP oil	8	13	18
Protox 166	5.5	6	6.5
Sulfur	1.5	1.5	1.5
Thermax (N 990)	20	20	20
Altax	1	1	1
Unads	0.3	0.3	0.3
Total:	139.3	144.8	150.3
Press cure (min @ °C)	15/150	15/150	15/150
Density (g/cm^3)	1.05	1.05	1.06

6. Shear Moduli

a. *Natural Rubber Formulation 334-289* (Ref. 36)

$$\log a_T = \frac{-5.85(T-5.00)}{79+T}$$

G′ (× 10⁶) Pa — G' (× 10⁶) Pa

G'' (× 10⁶) Pa

$\log \omega\, a_T$
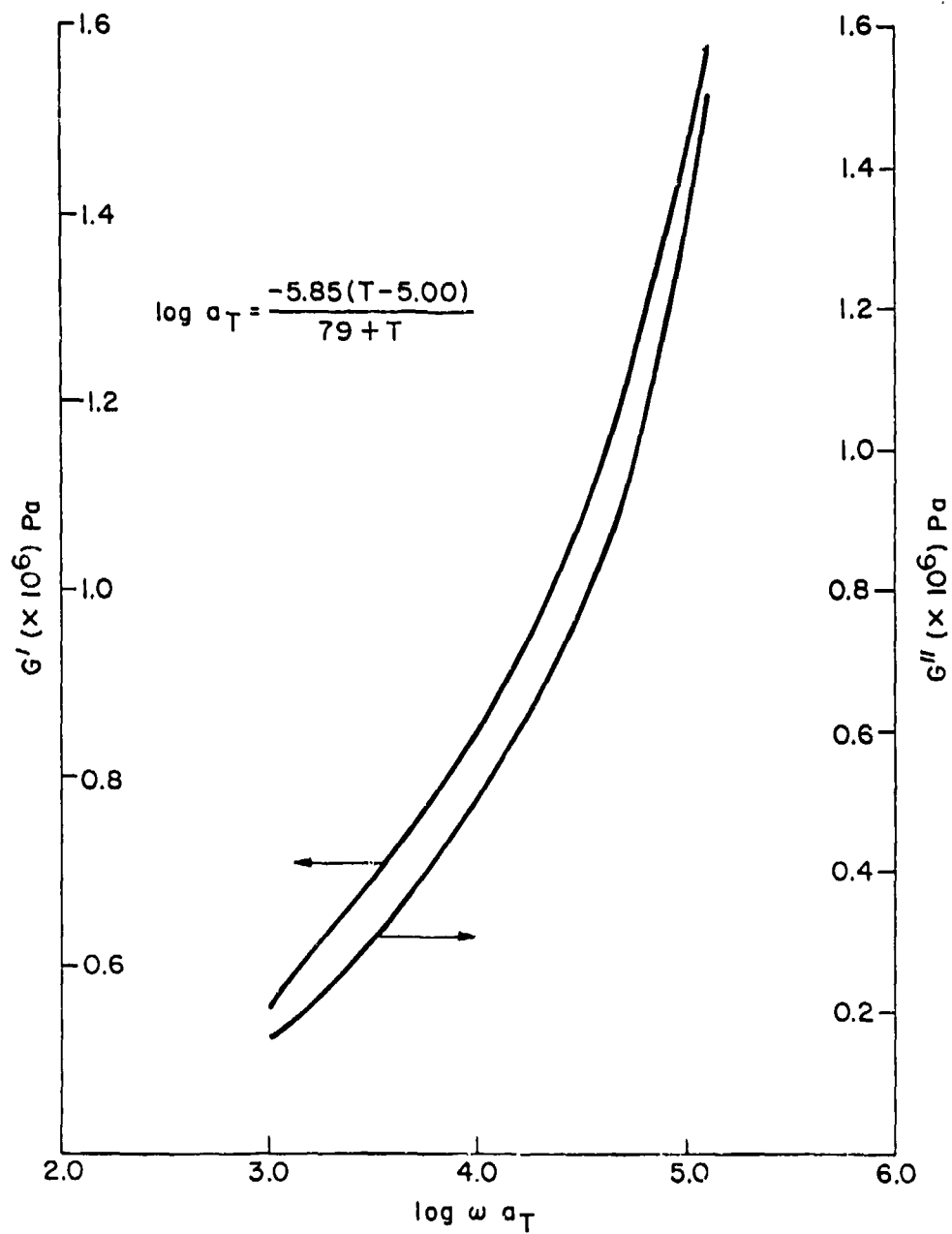
b. *Natural Rubber Formulation 334-290* (Ref. 36)

$$\log a_T = \frac{-6.09 (T-5.00)}{64.7 + T}$$

c. *Natural Rubber Formulation 334-291* (Ref. 36)

$$\log \ a_T = \frac{-6.42 \ (T-5.00)}{80.2+T}$$
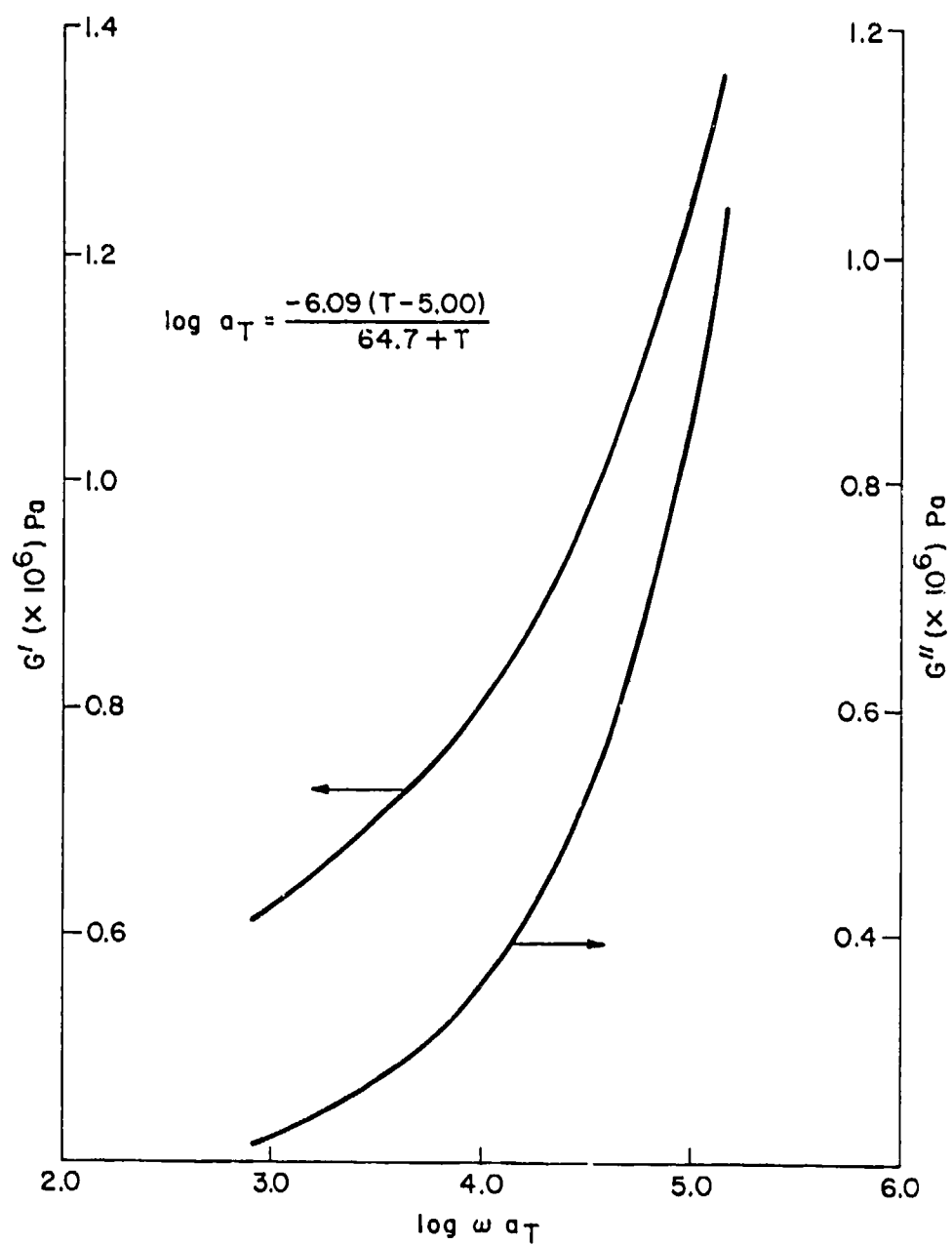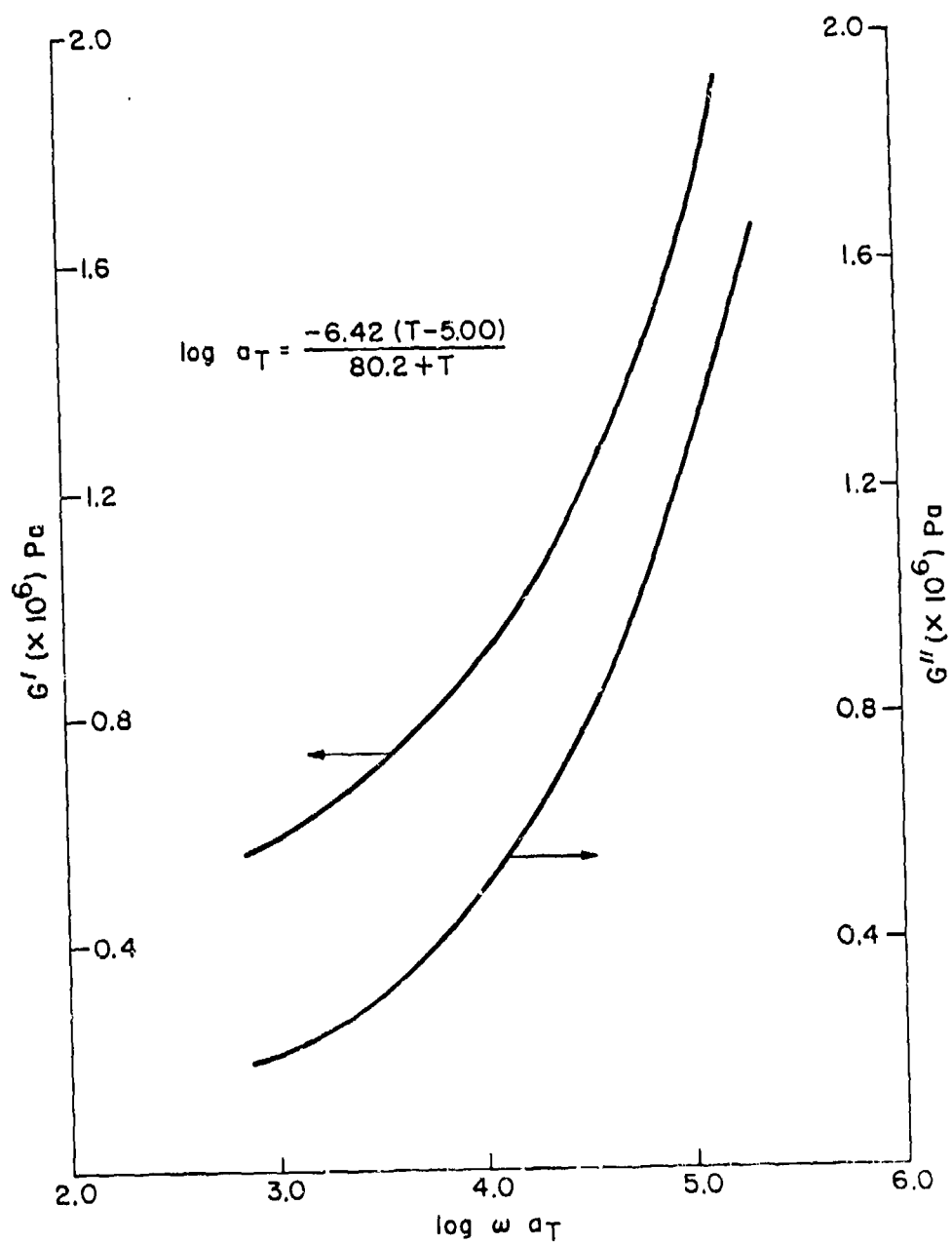
H. Neoprene Rubber (CR)

1. General Information and Characteristics

General Information:

General class of elastomers obtained by polymerization of 2-chloro-1,3-butadiene. There are many different types of neoprene with differentiation being based on the type of polymerization by which they were obtained. Type W and Type G are the two major subclassifications. Type W neoprenes have higher tensile properties and better storage stabilities than Type G. Subtypes WRT and GRT contain co-monomers for improved resistance to low temperature crystallization and hardening.

Vulcanization of neoprene compositions is dependent on the presence of metallic oxides. Typically zinc oxide and magnesium oxide are used in a ratio of 5 parts to 4 parts per 100 parts of base polymer. Type W neoprenes also require the addition of organic accelerators. Improved water resistance can be obtained by substituting lead oxide (litharge) for magnesium oxide at slightly higher load levels.

Unlike most synthetic rubbers, unfilled neoprene vulcanizates have good physical properties: however, fillers are generally used. Channel blacks generally give higher moduli and tensile strengths, but are difficult to process. Because of this higher loadings of furnace blacks, SRF and HMF blacks are frequently used.

Notable Characteristics:

High tensile strength, abrasion resistance, and adhesion to metal. Resistant to acids, ozone, weather, lube oils, alcohols, esters, ketones, and aliphatic solvents. Not as flexible at low temperatures as some other elastomers.

2. Physical Static Properties

	Hardness (Shore A)	
	40	65
Tensile Strength (MPa)	19.3	23.5
Ultimate Elong. . . on (%)	850 – 1050	550 – 750
300% Modulus (MPa)	1.3 – 2.6	4.5 – 7.6
Density (g/cm³)	1.24	1.40
Low Temperature Stiffness (°C) . . .	–23 to –29	–18 to –23
Coefficient of Thermal Expansion (cm/cm/°C)	4.5×10^{-4}	4.5×10^{-4}
Volume Resistivity (ohm-cm)	$\sim 10^{10}$	$\sim 10^{10}$
Dielectric Strength (kV/cm) . . .	59 – 236	59 – 236
Dielectric Constant	9 @ 1 kHz	9 @ 1 kHz
Water Absorption (%) (1 week at 20°C)	1.6 – 2.2	0.5 – 1.4
Water Permeability (38°C) $10^{-10} gH_2O$ cm/cm²-hr-torr	– –	440 (Type W)

3, Neop'___ 09

Manufactured by Burke Industries

Ingredient	Part
Neoprene GRT (duPont)	100
Prespersion B1631 (Ware Chemical)	15
Philblack N550	40
Octamine (Uniroyal)	2
Altax (Vanderbilt)	1.5
Stearic Acid	1

Cure: 20 minutes at 160°C

Vulcanizate density: 1.44 g/cm^3 at 25°C

Properties:

Shore A Hardness	69
Tensile Modulus (300%) (MPa)	11.0
Ultimate Elongation	570%
Tensile Strength (MPa)	19.3
Sound Speed (m/s at 1 MHz)	1643
Shear Modulus (Pa at 1.9 Hz)	5.97×10^6
Tan Delta	0.076

4. Compounding Ingredients for Neoprene Formulations

Philblack N-550 -- FEF Carbon Black -- Various Suppliers.

Altax -- Benzothiazyl disulfide -- R. T. Vanderbilt, New York, NY.

Thermax (N-990) -- ASTM Carbon Black N-990 -- Various Suppliers.

Prespersion B 1631 -- Red Lead with 10% napthenic oil -- Ware Chem.

Circosol 2XH -- ASTM oil #103 -- Sun Oil

Neozone D-N-phenyl-B-napthylamine (antioxidant) - DuPont

Octamine - Uniroyal Chemical Co.

Ingredients	Neoprene W (USRD)	Burke 5112	334-292	334-293	334-294
Neoprene Type W	60	-	-	-	-
Neoprene Type WB	40	-	-	-	-
Neoprene TRT	-	100	-	-	-
Neoprene GRT	-	-	100	100	100
Neozone D	2	-	-	-	-
Stearic Acid	7	0.3	1	1	1
Petrolatum	1	-	-	-	-
Light Calcium Magnesium	4	-	-	-	-
Thermax (MT Carbon Black)	100	-	20	30	50
Circo Light Oil	15	-	-	-	10
NA-22 (ethylene thiourea)	0.625	-	-	-	-
Zinc Oxide	6.25	-	-	-	-
Philblack N550	-	40	20	10	-
Altax	-	0.35	1.5	1.5	1.5
Sulfur	-	0.5	-	-	-
Prespersion B 1631 (Red lead)	-	15	15	15	15
Octamine	-	1	2	2	2
Thionex	-	1	-	-	-
Total:	235.9	158.2	159.5	159.5	179.5
Press cure (min @ °C)	30/153	30/160	20/160	20/160	20/160
Density (g/cm^3)	1.44	1.46	1.45	1.45	1.45

5. Shear Moduli

    a.   *USRD Neoprene W*   (Ref. 32)

$$\log a_T = \frac{-2.78(T-10.00)}{36.2 + T}$$
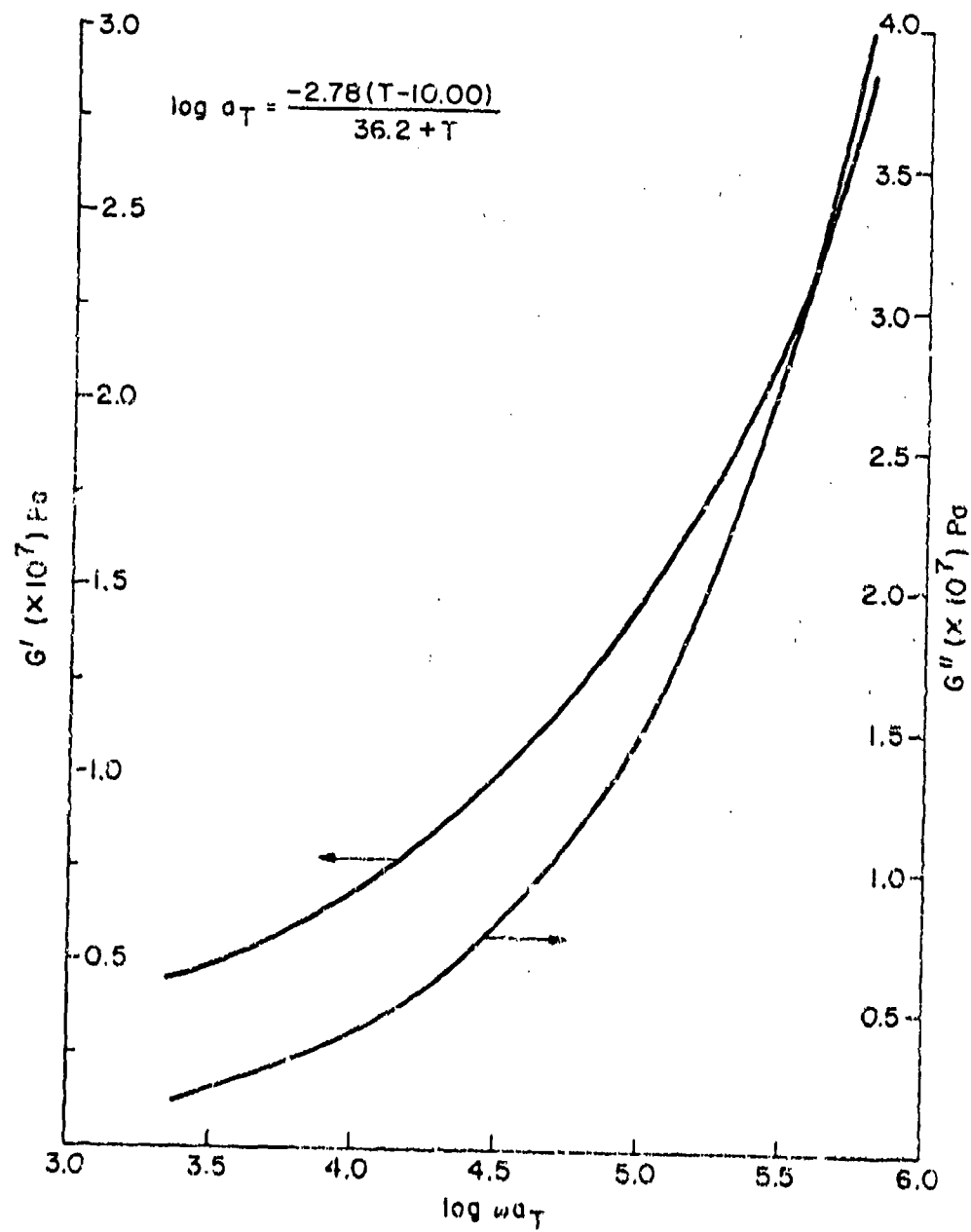
b. *Burke Formulation* 5112 (Ref. 37)

$$\log a_T = \frac{-8.85(T-10.00)}{107+T}$$
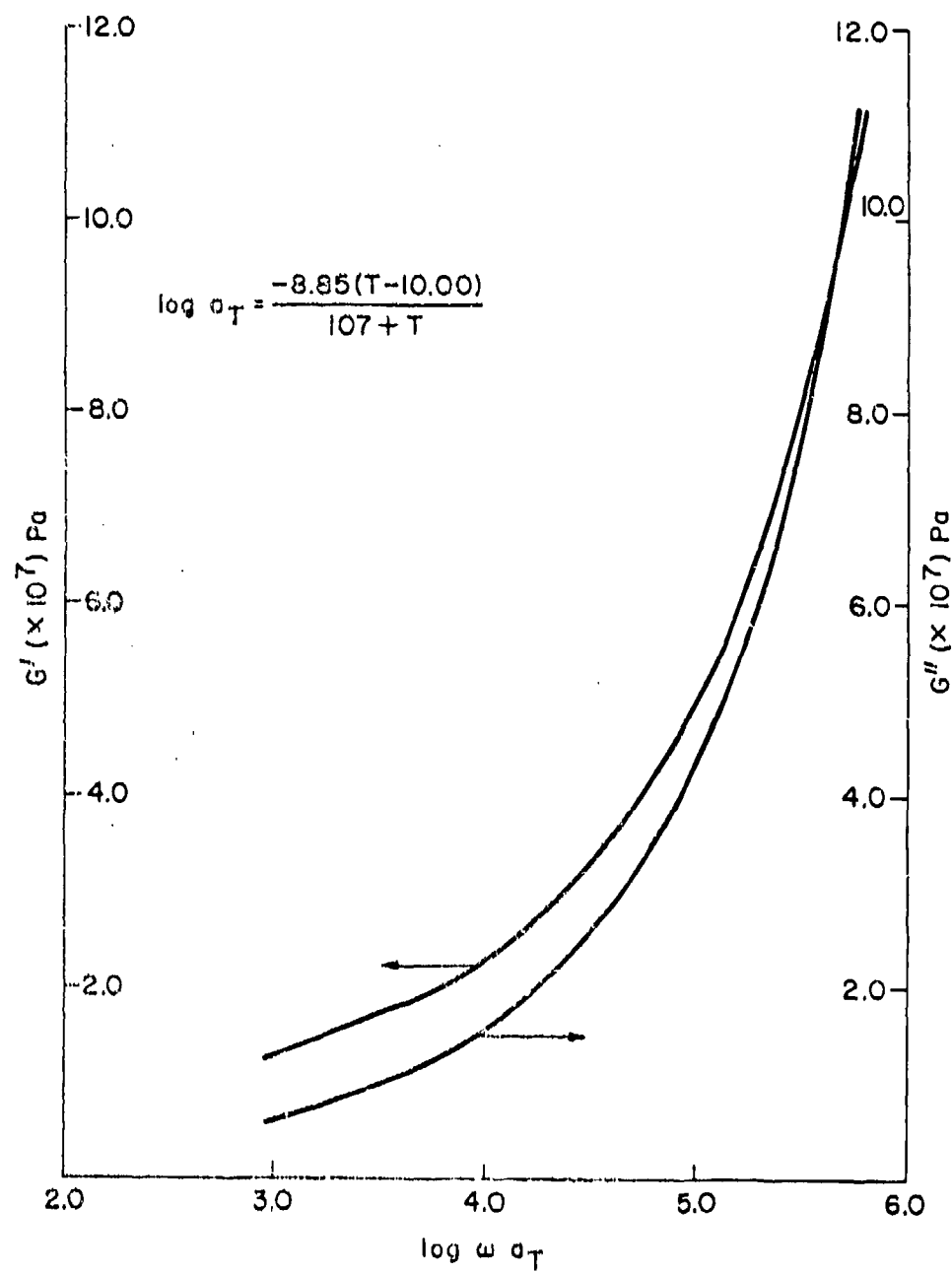
c. *Neoprene Formulation 334-292* (Ref. 36)

$$\log a_T = \frac{-6.04\,(T-5.00)}{60.3 + T}$$

75
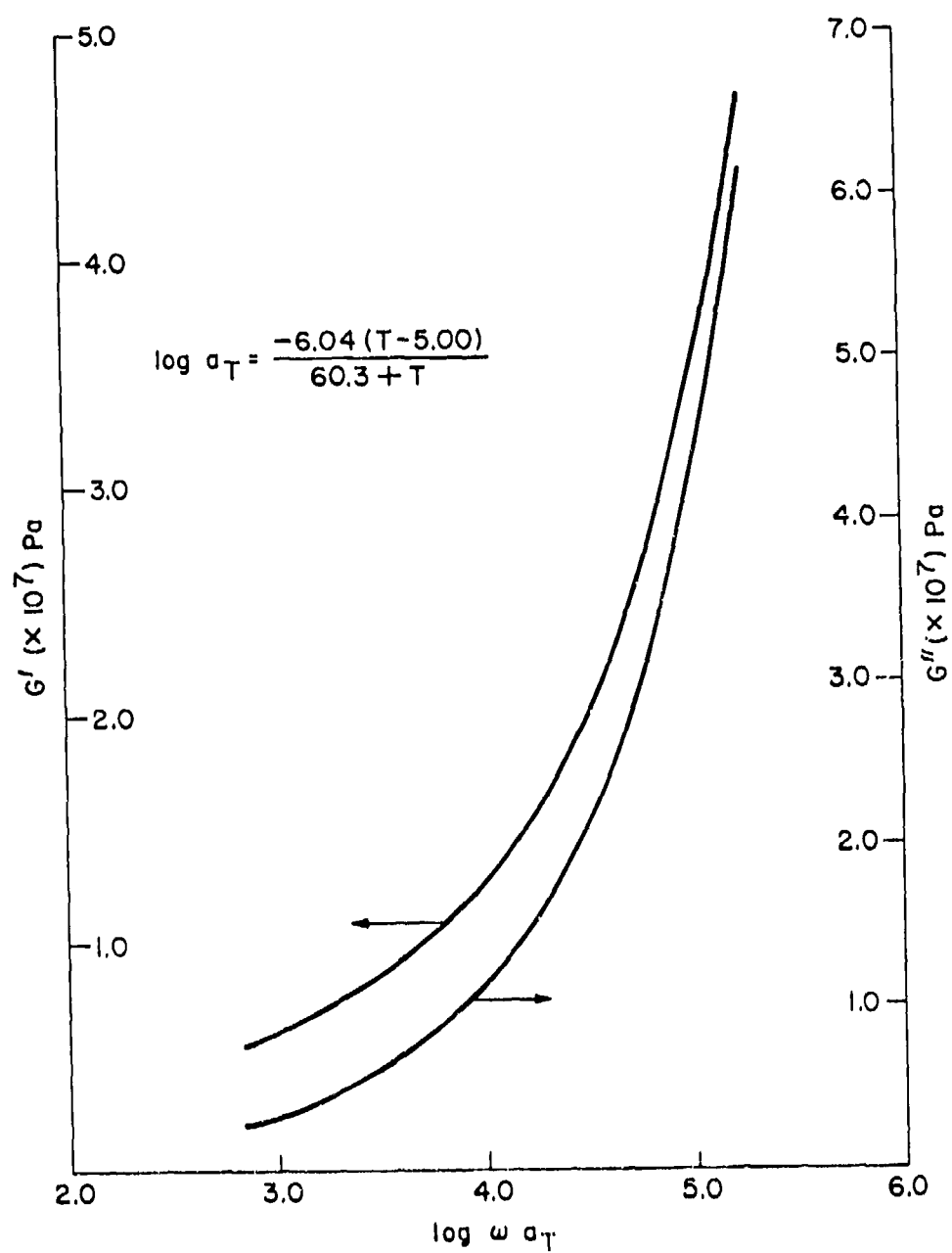
d. *Neoprene Formulation 334-293* (Ref. 36)

$$\log a_T = \frac{-6.38\,(T-5.00)}{63.2+T}.$$
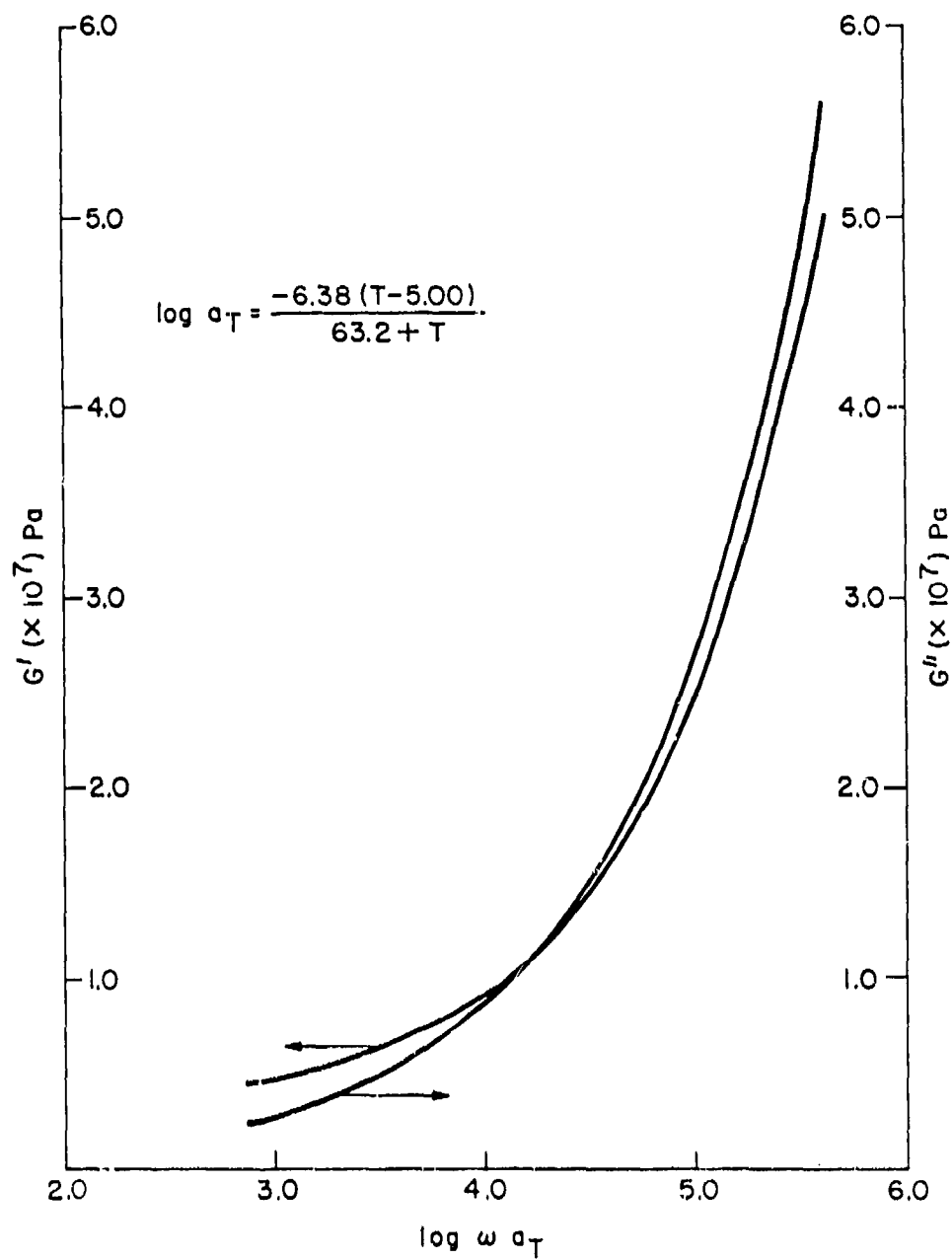
e. *Neoprene Formulation 334-294* (Ref. 36)

$$\log a_T = \frac{-7.87(T-5.00)}{88.4 + T}$$
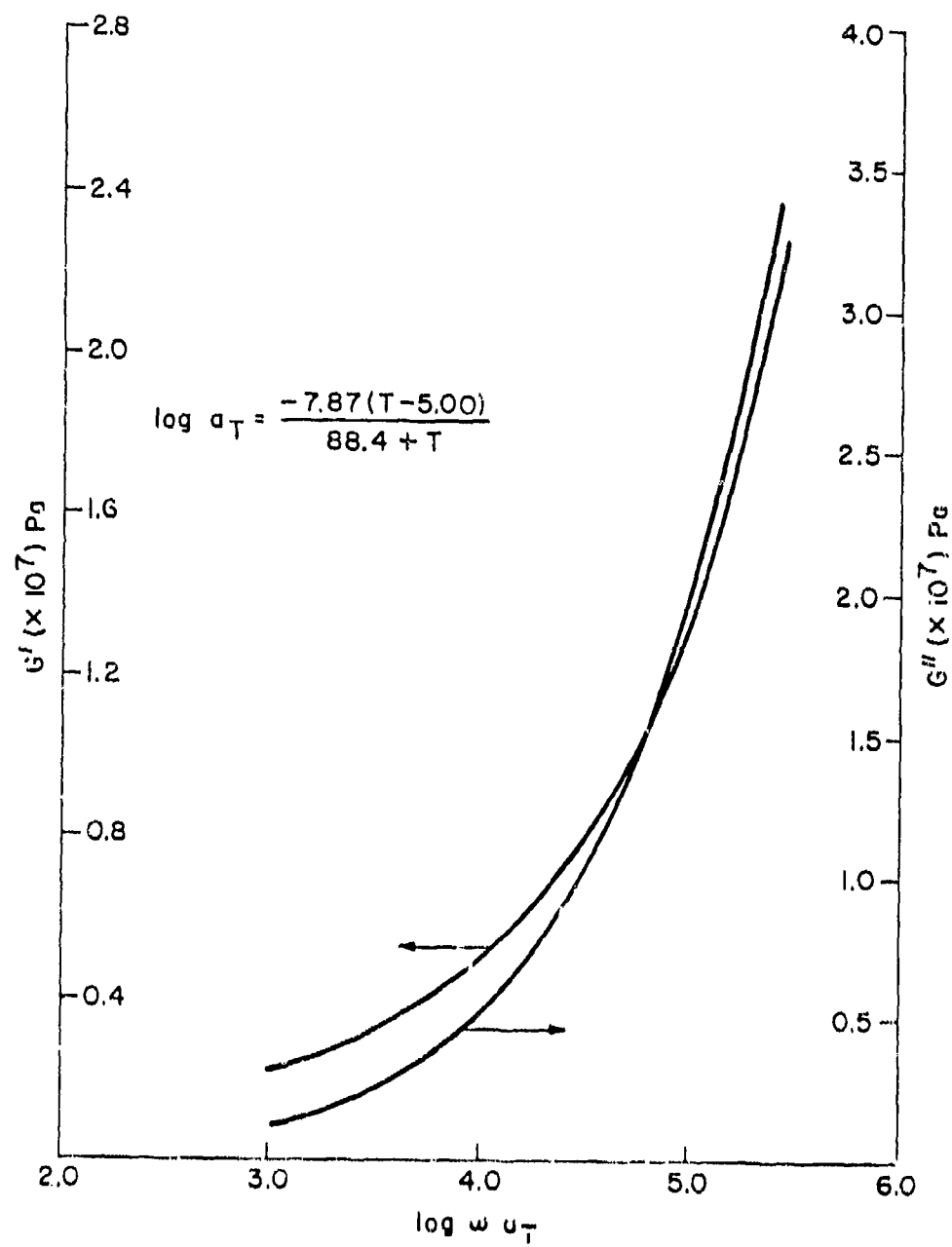
I. Nitrile Rubber (NBR, Buna-N)

1. General Information and Characteristics

General Information: Nitrile rubber is a copolymer of butadiene
                        with acrylonitrile. Grades differ accord-
                        ing to their acrylonitrile content, which
                        is the determining factor in final vulcani-
                        zate properties.

                        Nitriles offer excellent resistance to oils
                        and hydrocarbon solvents. Oil, solvent
                        resistance, and cost increase with acrylo-
                        nitrile content while resilience, low-
                        temperature flexibility, and ozone resistance
                        decrease.

                        Nitrile rubbers may be vulcanized in the
                        conventional manner with sulfur and acceler-
                        ator, however, more accelerator and less
                        sulfur are used than with natural rubber or
                        butyl compositions. Gum stocks may also be
                        vulcanized with dicumyl peroxide for vulcani-
                        zates with better low-temperature properties.
                        Pure gum vulcanizates have poor strength
                        properties, therefore, the use of reinforc-
                        ing fillers is required.

                        Electrical properties of nitriles are medi-
                        ocre, not for use as primary insulation.

Notable Characteristics: Resistance to oils and hydrocarbon solvents.
                        High strength and abrasion resistance.

                        Limited low-temperature applicability due
                        to stiffening, prone to ozone cracking;
                        poor resistance to ketone, ester, and
                        aromatic hydrocarbon solvents.

2. Physical Static Properties

        The physical properties of Nitrile rubber vulcanizates are parti-
cularly dependent upon the acrylonitrile content of the gum stock. To illustrate
this, the physical properties of two compounds are presented. These compounds
are identical except for the acrylonitrile contents of the base polymer.

Compound A Recipe			Compound B Recipe	
Ingredient	Parts		Ingredient	Parts
Chemigum N-3 (40% acrylonitrile)	100.0		Chemigum N-7 (33% acrylonitrile)	100.0
Zinc Oxide	5.0		Zinc Oxide	5.0
Stearic Acid	1.0		Stearic Acid	1.0
HAF Black	50.0		HAF Black	50.0
Altax	2.0		Altax	2.0
Methyl Tuads	1.0		Methyl Tuads	1.0
Sulfur	0.3		Sulfur	0.3

Cured 9 min. at 176°C (350°F)   Cured 9 min. at 176°C (350°F)

Properties	Compound A	Compound B
Tensile Strength (MPa)	28.6	25.9
Ultimate Elongation (%)	330	310
300% Modulus (MPa)	26.2	24.1
Density (g/cm^3)	1.21	1.18
Low-Temperature Stiffness (°C)	15 to −23	‥18 to −23
Volumetric coefficient of Thermal Expansion (cm^3/g·°C)	8.4×10^{-4}	9.7×10^{-4}
Volume Resistivity (ohm−cm)	$\sim 10^{10}$	$\sim 10^{10}$
Dielectric Strength (kV/cm)	91	99
Dielectric Constant	1.4	15
Hardness (Shore A)	79	75

3. Compounding Recipe

The gum vulcanizate of the accompanying figure was prepared according to the following recipe:

Ingredient	Parts
Hycar OR-15 (now Hycar 1001)	100.0
Zinc Oxide	5.0
Benzothiazyl disulfide	1.3
Sulfur	1.5

Samples were molded at 143°C (289.4°F) for 60 minutes. The density of the cured material is 1.05 g/cm^3 at 20°C, and the volumetric thermal expansion coefficient is 1.2×10^{-3} cm^3/g·°C, between 0 and 80°C.

Note that this material does not contain any carbon black. For most practical applications, nitrile rubber vulcanizates contain carbon black or some inorganic additive to improve its physical properties. The presence of these additives increases the moduli of the materials by 20-30% or more over the moduli of the unfilled gum vulcanizates. Because of this, the modulus values obtained from this the accompanying figure should be multiplied by 1.25 or 1.30 in order to obtain moduli representative of a more realistic nitrile rubber vulcanizate.

4. Longitudinal Modulus of Nitrile Rubber, Unfilled (Ref. 30)

$$T_R = 10°C$$

$$\log a_T = \frac{-11.3\,(T-10.0)}{T+222.5}$$
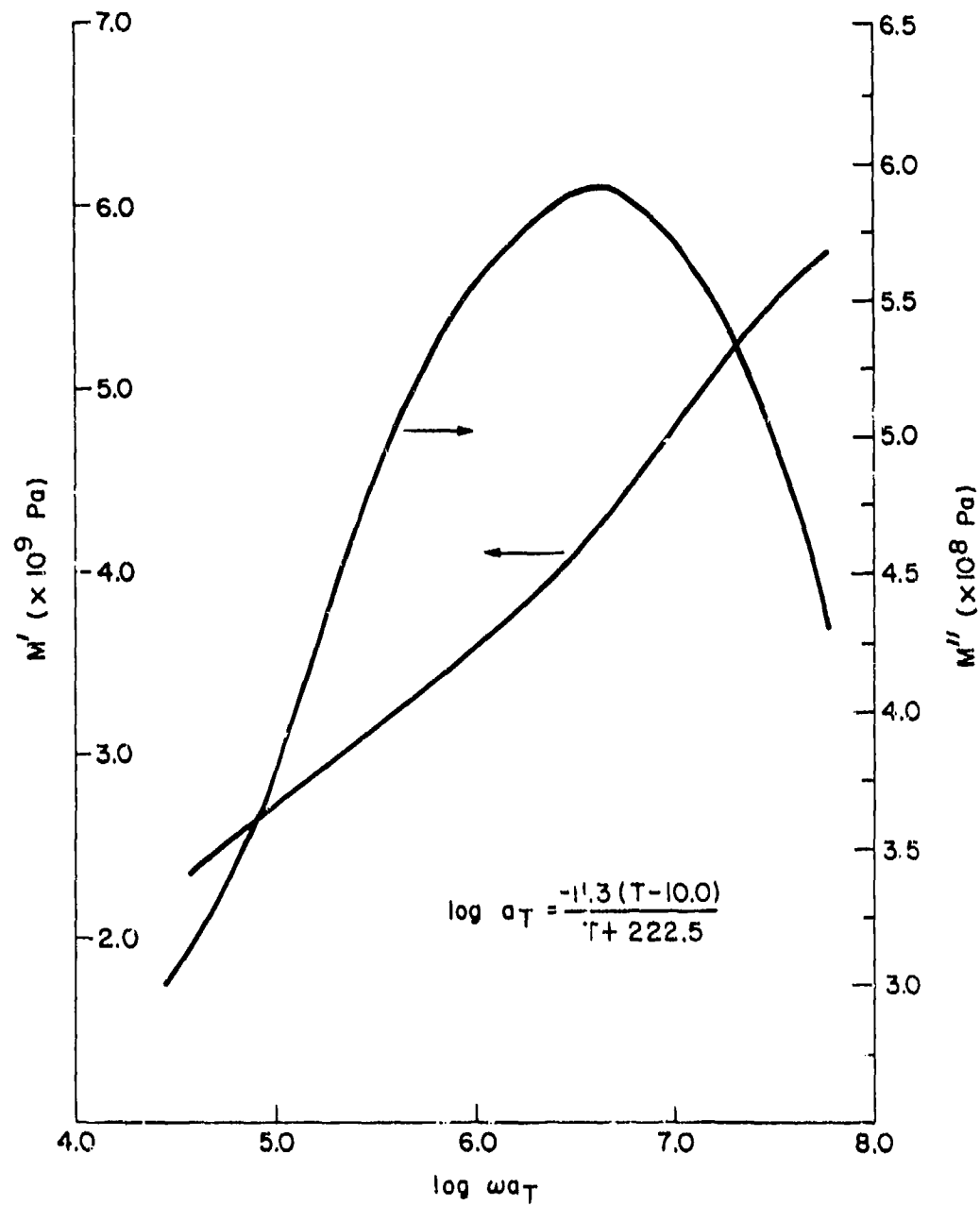
5. Compounds Used in Nitrile Formulations (Ref. 10)

Elastomers:

Hycar 1034-60--acrylonitrile content 21%
Hycar 1203--70/30 blend of butadiene-acrylonitrile/polyvinyl chloride
Paracril BLT--acrylonitrile content 32%
Paracril CLT--acrylonitrile content 38%

Vulcanizing Agents--Peroxides

Di Cup 40--Hercules, dicumyl peroxide, sp. gr. 1.607, peroxide content 39.5-41.5%
Saret 500 + 515--Sartomer, acrylic crosslinking agent, liquid polymerisable monomer, sp. gr. 1.08, B.p. 200°C
Vul-Cup 40 KE--Hercules, $\alpha - \alpha'$ - bis (t-butylperoxyl) diisopropylbenzene, sp. gr. 1.03, peroxide content 96-100%

Sulfur (Rubbermakers or Tire 21-12 MC-TP) vulcanizing agent, sp. gr. 2.07

Carbon Blacks:

Philblack N-330--Phillips Chemical, HAF, average particle size 30 mμ, surface area 81m^2/g
Philblack N-358--Philips Chemical, SPF, average particle size 25 mμ, surface area 87 m^2/g
Regal 99 (N-440)--Cabot, FF, average particle size 43 mμ, surface area 60m^2/g
Philblack N-550--Phillips Chemical, FEF, average particle size 41mμ, surface area 43m^2/g
Thermax--RT Vanderbilt, MT, average particle size 320-472mμ, surface area 8.2 m^2/g, density kg/m^3
United N234--Ashland Chemical Company, ISAF, average particle size 21 mμ, surface area, 121m^2/g, density 320 kg/m^3

Non-Black Fillers:

Andrez 8000AE, Anderson, Polystyrene resin
Hil-Sil 223-Harwick Chemical, precipitated, hydrated silica, sp. gr. 2.0, ultimate particle size 0.022 micron
Iron Oxide--Black iron oxide, painter's grade
Quso WR 82--Philadelphia Resins, Surface-treated silica pigment
Titanium Dioxide--Whitener, medium grade

Table 7, Part 1: Nitrile Rubber Formulations

Material	314-818	314-1057	314-1058	314-1059	314-1060	314-1061	314-1062	314-1063
PARACRIL CLT	100	100	100	100	100	100	100	100
PHILBLACK N-550	50	70	-	-	20	20	-	-
THERMAX	-	-	80	120	-	-	-	-
IRON OXIDE	-	-	-	-	100	200	-	-
QUSO WR 82	-	-	-	-	-	-	30	50
STEARIC ACID	1	1	1	1	1	1	1	1
PROTOX 166	5	5	5	5	5	5	5	5
FYROL CEF	5	5	5	5	5	5	5	5
OCTAMINE	1	1	1	1	1	1	1	1
THIONEX	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
SULFUR	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Total parts by weight	164	184	194	234	234	334	144	164

Table 7, Part 2: Nitrile Rubber Formulations

Material	314-983	314-1064	314-1065	314-1066	314-1067	314-1068	314-1069	314-1070
PARACRIL BLT	100	-	-	-	-	-	-	-
PARACRIL CLT	-	100	100	100	100	100	100	100
PHILBLACK N-550	50	50	50	50	50	50	50	50
STEARIC ACID	1	-	-	-	-	-	-	-
PROTOX 166	5	5	5	5	5	5	-	5
FYROL CEF	5	-	-	-	-	-	-	-
OCTAMINE	1	2	2	2	2	2	2	2
THIONEX	0.5	-	-	-	-	-	-	-
SULFUR	1.5	-	-	-	-	-	-	-
TE 28 G9	0.9	-	-	-	-	-	-	-
SARET 500	-	-	5	10	20	-	-	-
SARET 515	-	-	-	-	-	3	10	20
DI CUP 40 PEROXIDE	-	4	4	4	4	4	4	4
Total parts by weight	164.5	161	156	171	181	166	171	181

Table 7, Part 3: Nitrile Rubber Formulations

Material	314-1073	314-1074	314-1075	314-1076	314-1077	314-1078	314-1079	314-1080
PARACRIL CLT	100	80	70	60	100	80	70	60
ANDREZ 8000AE	-	20	30	40	-	20	30	40
PHILBLACK N-330	-	-	-	-	30	30	30	30
STEARIC ACID	1	1	1	1	1	1	1	1
PROTOX 166	5	5	5	5	5	5	5	5
FYROL CEF	5	5	5	5	5	5	5	5
OCTAMINE	1	1	1	1	1	1	1	1
THIONEX	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
SULFUR	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Total parts by weight	114	114	114	114	144	144	144	144

Table 7, Part 4: Nitrile Rubber Formulations

Materials	1474	1476	1477	1478	1479	1480	1481
PARACRIL CLT	100	100	100	100	100	100	100
PHILBLACK N-358	-	40	-	-	-	-	-
PHILBLACK N-330	-	-	40	-	-	-	-
PHILBLACK N-440	-	-	-	40	-	-	-
QUSO WR 82	-	-	-	-	40	-	-
Hi-SIL 223	-	-	-	-	-	40	-
TI O_2	-	-	-	-	-	-	40
AGE RITE RESIN D	0.5	0.5	0.5	0.5	0.5	0.5	0.5
PROTOX 166	5.0	5.0	5.0	5.0	5.0	5.0	5.0
STEARIC ACID	1.0	1.0	1.0	1.0	1.0	1.0	1.0
VUL-CUP 40 KE	1.5	3.0	3.0	3.0	3.0	3.0	3.0
Total parts by weight	108.0	149.5	149.5	149.5	149.5	149.5	149.5

Table 7, Part 5: Nitrile Rubber Formulations

Material	1489	1492
HYCAR 1411, CROSSLINKED	100	100
PARACRIL CLT	-	-
PHILBLACK N-330	40	-
AGE RITE RESIN D	0.5	0.5
PROTOX 166	5.0	5.0
STEARIC ACID	1.0	1.0
VUL-CUP 40 KE	3.0	3.0
Total parts by weight	149.5	109.5

Table 7, Part 6: Nitrile Rubber Formulations

Material	1507	1508	1509
HYCAR 1203, (70 NBR, 30 PVC)	100	100	100
PHILBLACK N-330	-	-	40
AGE RITE RESIN D	-	-	0.5
PROTOX 166	-	-	5.0
STEARIC ACID	-	-	1.0
VUL-CUP 40 KE	-	3.0	3.0
Total parts by weight	100	103.0	149.5

Table 7, Part 7: Nitrile Rubber Formulations

Material	NA 440
HYCAR 1034-60	100
UNITED N234	40
DIOCTYL PHTHALATE	15
ST. JOE 42-41	3
MBTS	1.5
STEARIC ACID	1
AGE RITE STALLITE	1
Total parts by weight	163

Table 7, Part 8: Nitrile Rubber Formulations

Material	314-1098	314-1099	314-1100	314-1101
PARACRIL CLT	100	-	-	-
PROTOX 166	5	5	5	5
PHILBLACK N-550	15	50	50	45
Fe_2O_3	100	-	-	-
PARACRIL BLT	-	100	50	100
PARACRIL KLT	-	-	50	-
OCTAMINE	2	1	1	1
STEARIC ACID	1	1	1	1
DIBUTYL PHTAHLATE	15	-	-	-
POLYVINYL ACETATE	15	-	-	-
DICUMYL PEROXIDE ON CALCIUM CARBONATE	6	-	-	-
FYROL CEF	-	5	5	10
SULFUR	-	1.5	1.5	1.5
TETRA METHYL THIURAM MONOSULFIDE	-	0.5	0.5	0.5
TE 2869	-	0.5	0.5	0.5
Total parts by weight	359	164.5	164.5	164.5

Table 8 - Density of Nitrile Rubber Compounds

Material	Density g/cm^3	Press Cure (Min @ °C)	Material	Density g/cm^3	Press Cure (Min @ °C)
314-818	1.22	25/160	1474	1.05	25/160
314-1057	1.27	25/160	1476	1.19	25/160
314-1058	1.29	25/160	1477	1.19	25/160
314-1059	1.37	25/160	1478	1.19	25/160
314-1060	1.69	25/160	1479	1.21	25/160
314-1061	2.10	25/160	1480	1.21	25/160
314-1062	1.18	25/160	1481	1.31	25/160
314-1063	1.24	25/160	1489	1.22	25/160
314-983	1.20	25/160	1492	1.09	25/160
314-1064	1.22	25/160	1507	1.08	25/160
314-1065	1.22	25/160	1508	1.09	25/160
314-1066	1.22	25/160	1509	1.25	25/160
314-1067	1.22	25/160	NA 440	1.13	25/160
314-1068	1.22	25/160	314-1098	1.99	15/160
314-1069	1.23	25/160	314-1099	1.16	25/160
314-1070	1.22	25/160	314-1100	1.15	25/160
314-1073	1.07	25/160	314-1101	1.13	25/160
314/1074	1.08	25/160			
314/1075	1.08	25/160			
314/1076	1.08	25/160			
314-1077	1.17	25/160			
314-1078	1.17	25/160			
314-1079	1.18	25/160			
314-1080	1.18	25/160			

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6. Nitrile Rubber – Varying Percentages of Acrylonitrile
(Shear Moduli)

a. *Nitrile Rubber Formulation* 314-818   (Ref. 10)

$$\log a_T = \frac{-5.48(T-10.00)}{46+T}$$
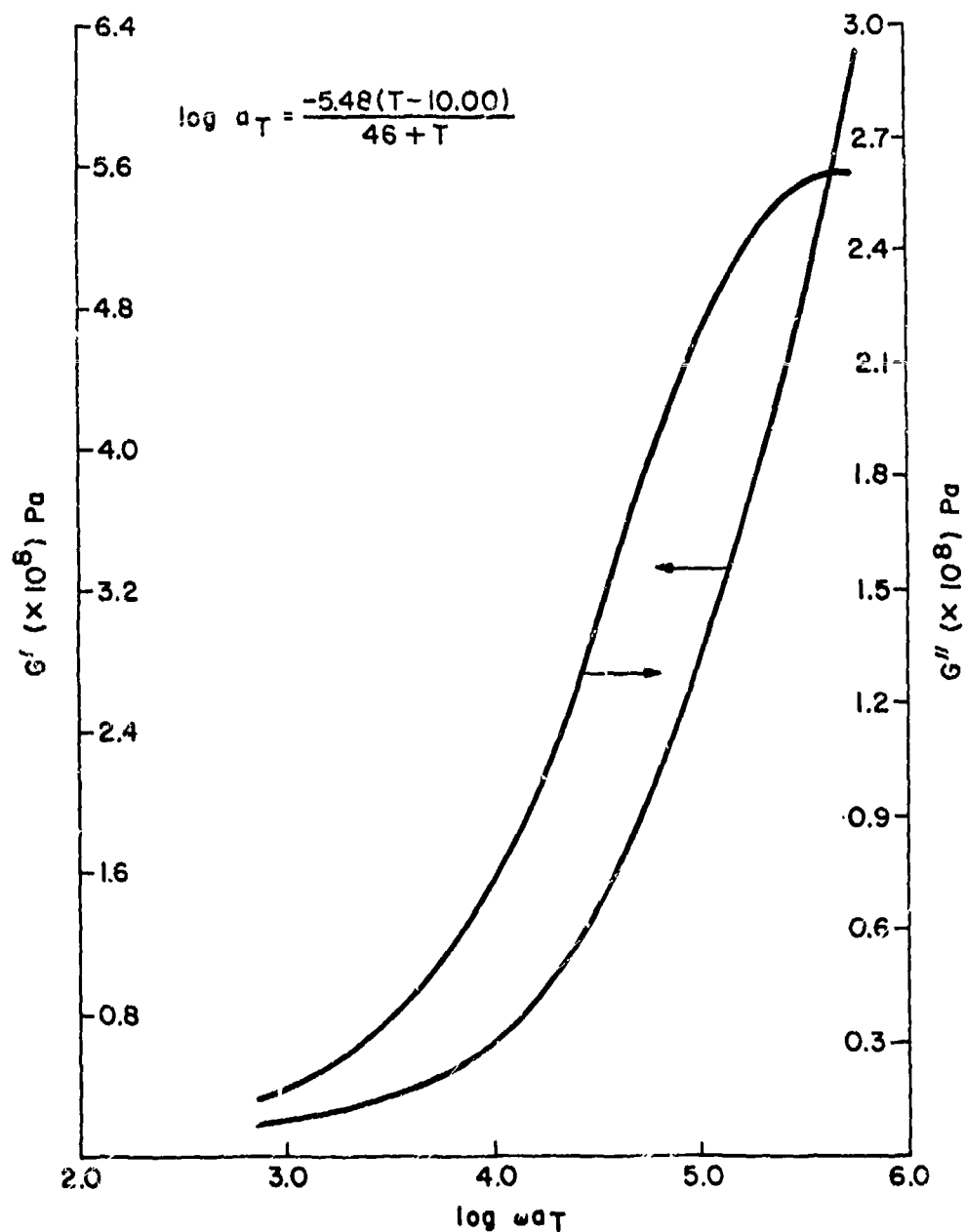
b. *Nitrile Rubber Formulation* 314-983   (Ref. 10)

$$\log a_T = \frac{-3.2\,(T-10.00)}{57+T}$$
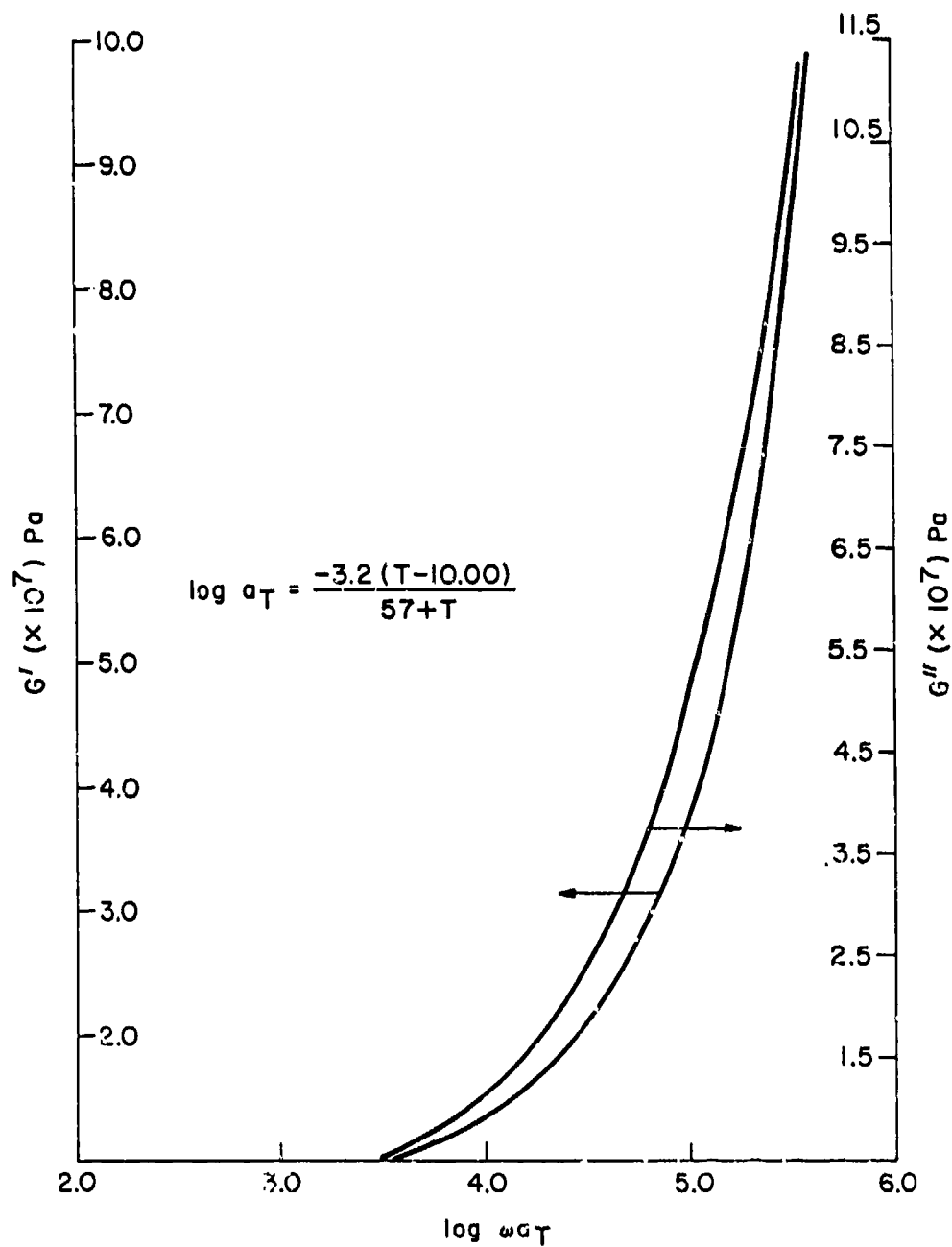
c. *Nitrile Formulations* 314-1057 *through* 314-1063

(1) Nitrile Rubber Formulation 314-1057
(Ref. 10)

$$\log a_T = \frac{-8.71(T-10.00)}{96+T}$$
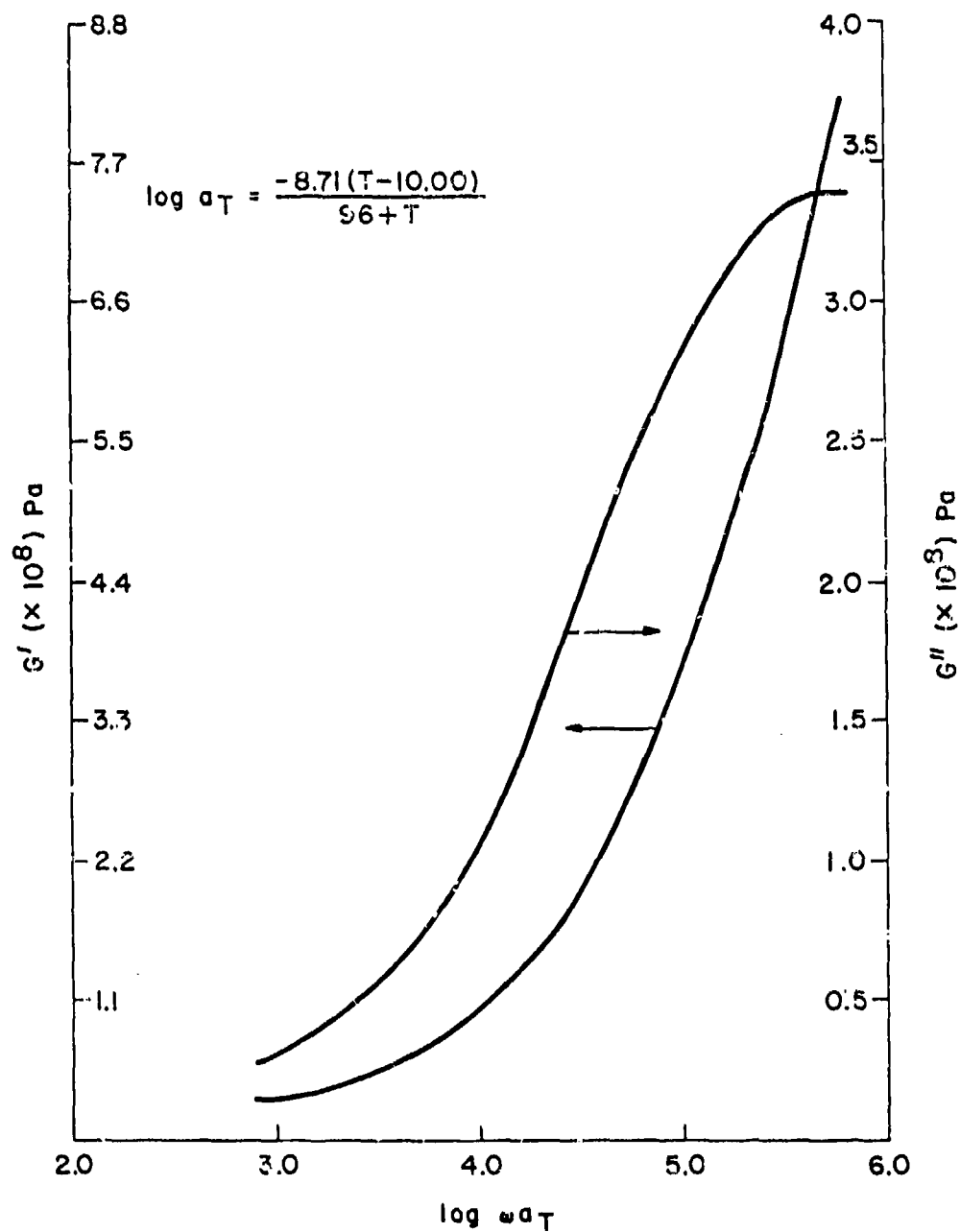
(2) Nitrile Rubber Formulation 314-1058
(Ref. 10)

$$\log a_T = \frac{-19(T-10.00)}{210-T}$$
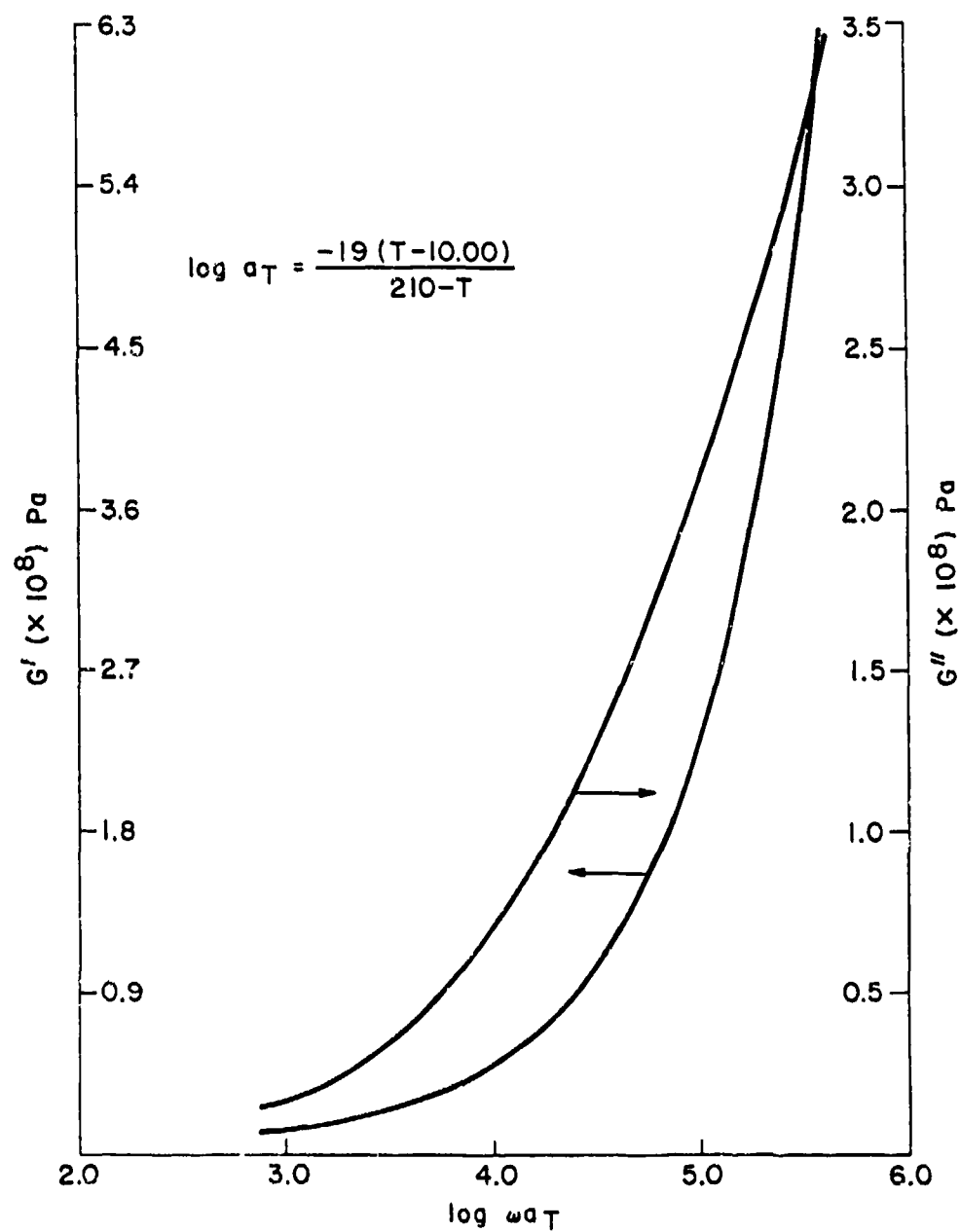
(3) Nitrile Rubber Formulation 314-1059
(Ref. 10)

$$\log a_T = \frac{-4.2\,(T-10.00)}{36+T}$$
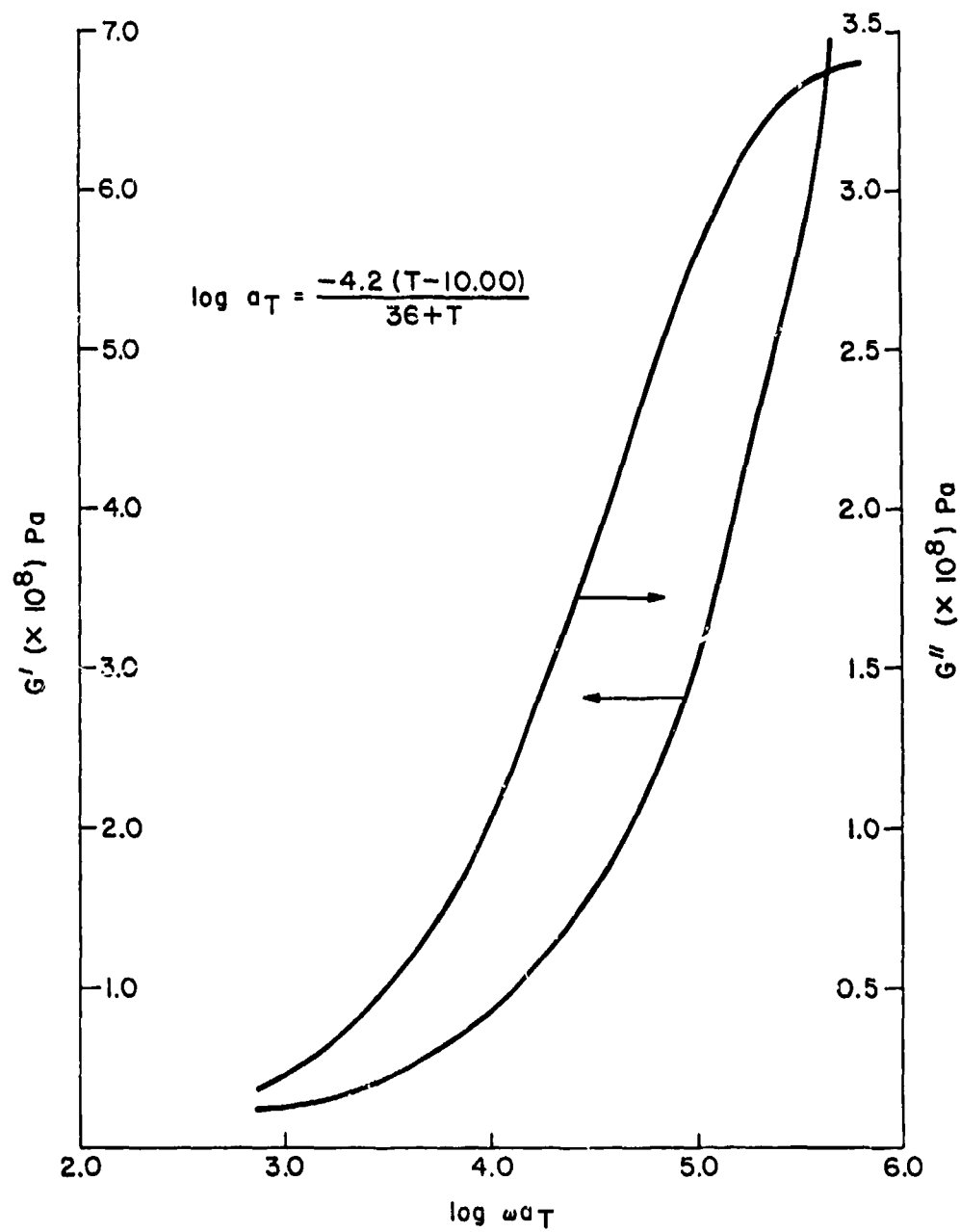
(4) Nitrile Rubber Formulation 314-1060

$$\log a_T = \frac{-7.76\,(T-10.00)}{71+T}$$
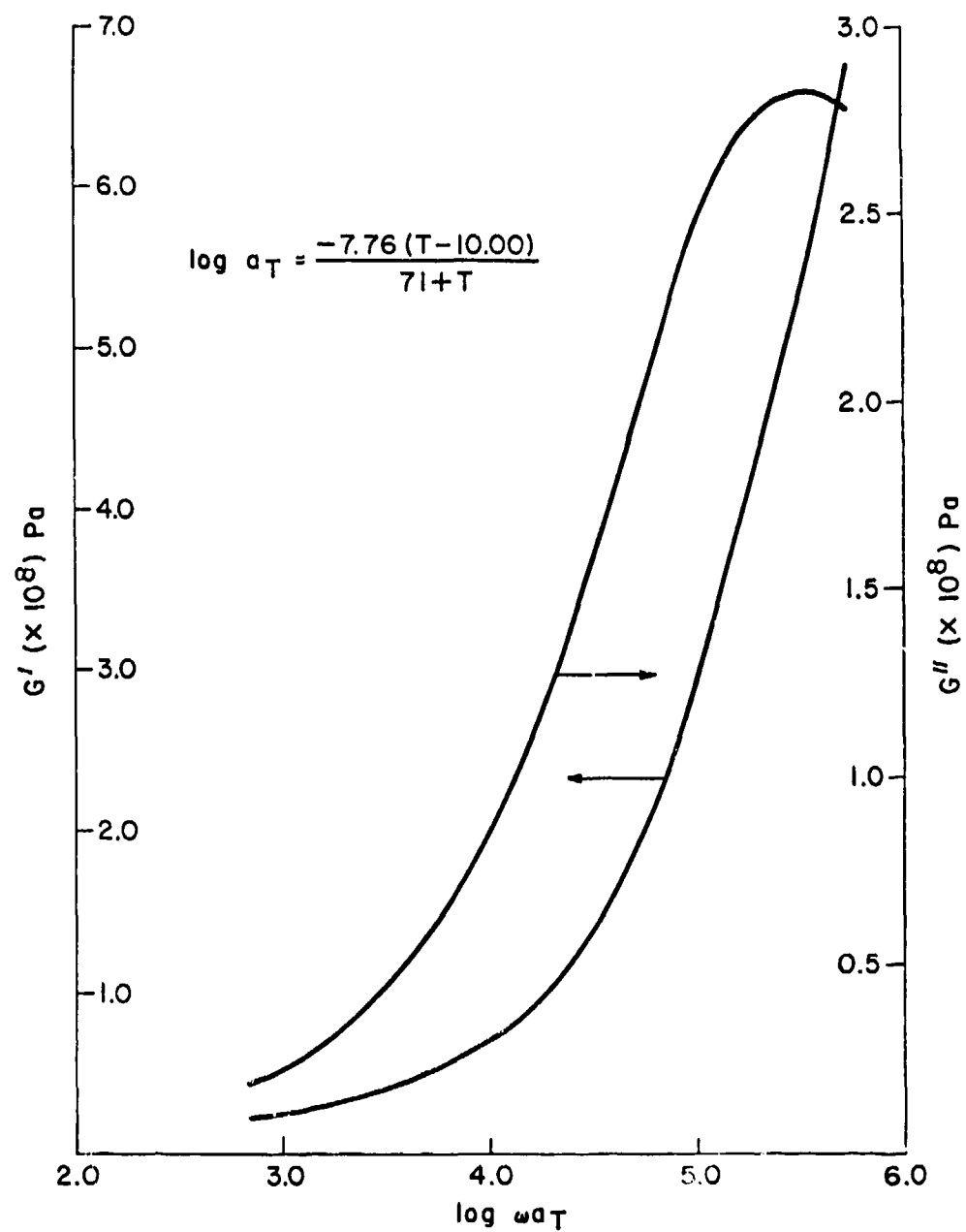
(5)   Nitrile Rubber Formulation 314-1061

(Ref. 10)

$$\log a_T = \frac{-2.84\,(T-10.00)}{20+T}$$
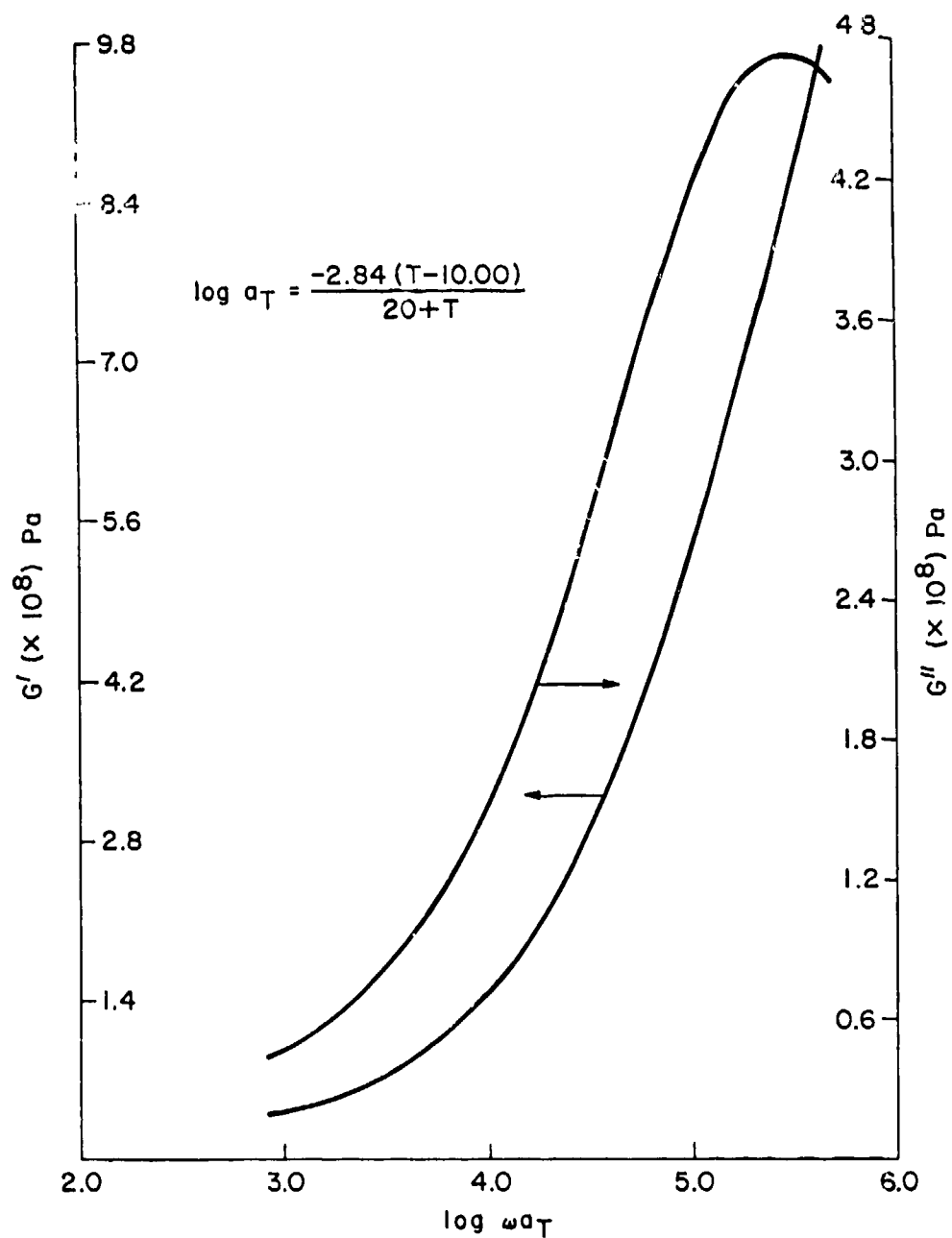
(6) Nitrile Rubber Formulation 314-1062
(Ref. 10)

$$\log a_T = \frac{-4.6\ (T-10.00)}{35+T}$$
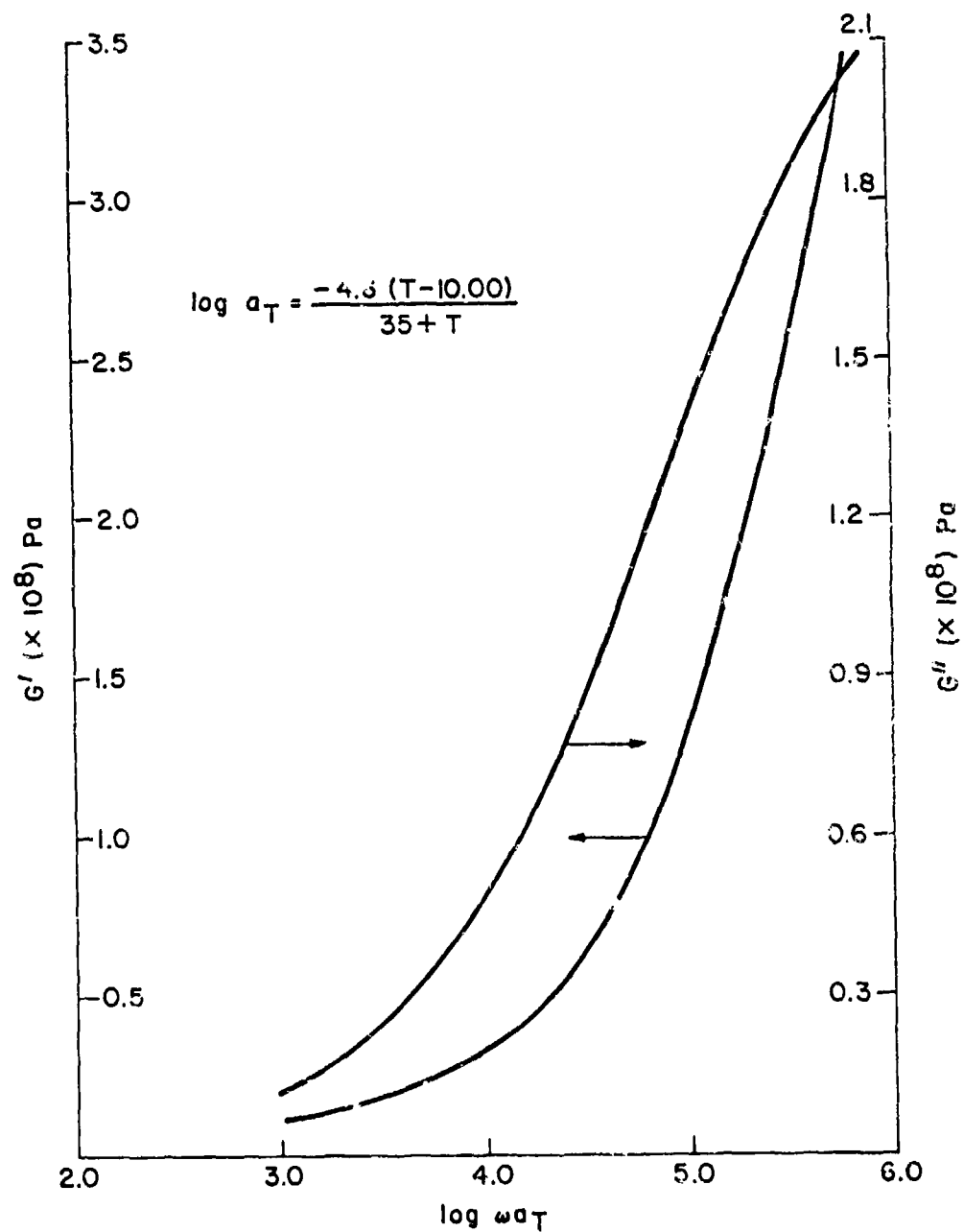
(7) Nitrile Rubber Formulation 314-1063
(Ref. 10)

$$\log a_T = \frac{-7.18\,(T-10.00)}{83+T}$$
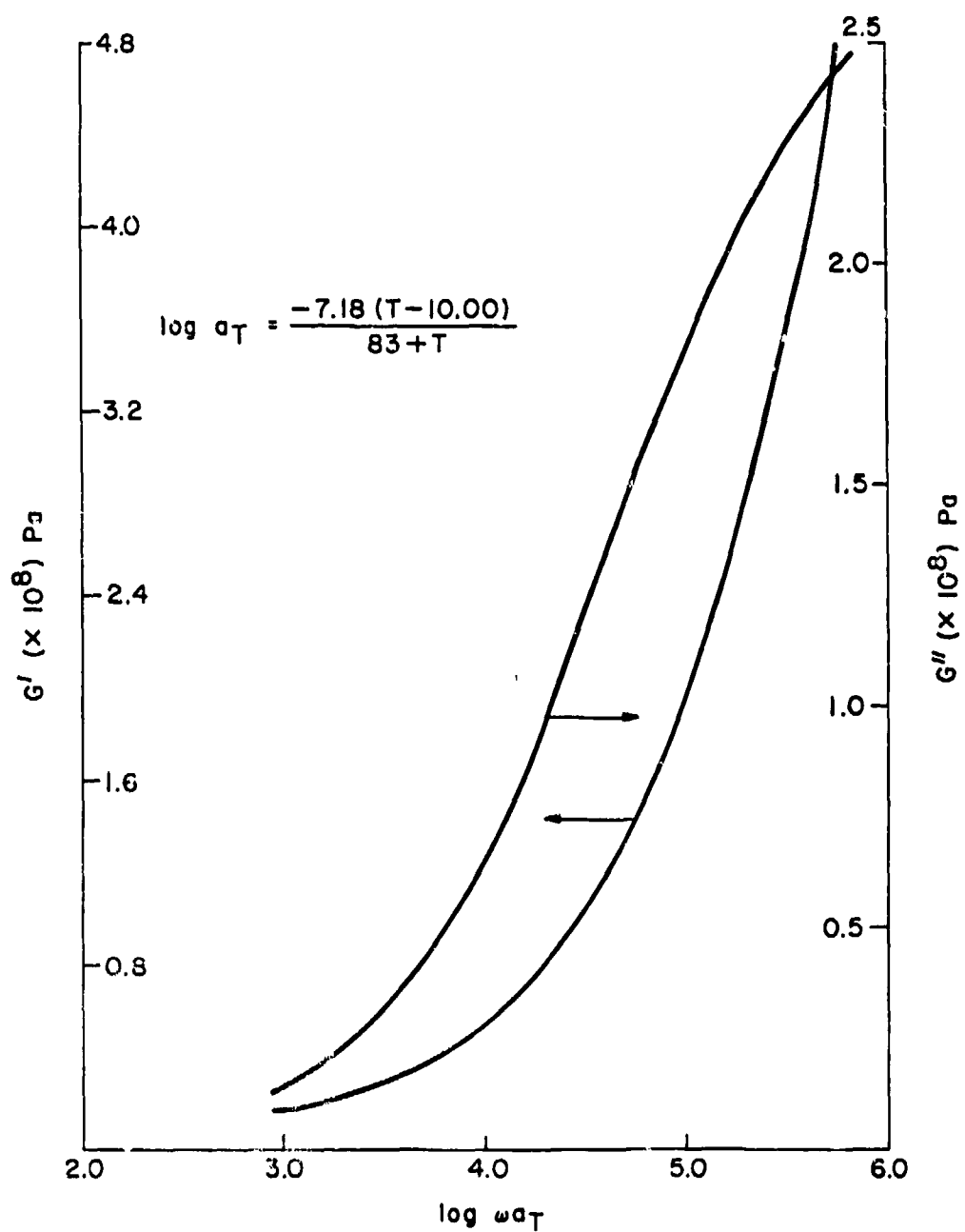
d. *Nitrile Formulation* 314-1064 *through* 314-1070, 1073 *through* 1075, *and* 1077 *through* 1080

(1) Nitrile Rubber Formulation 314-1064

(Ref. 10)

$$\log a_T = \frac{-6.3(T-10.00)}{83+T}$$

$$\log a_T = \frac{-10.6\,(T-10.00)}{119+T}$$
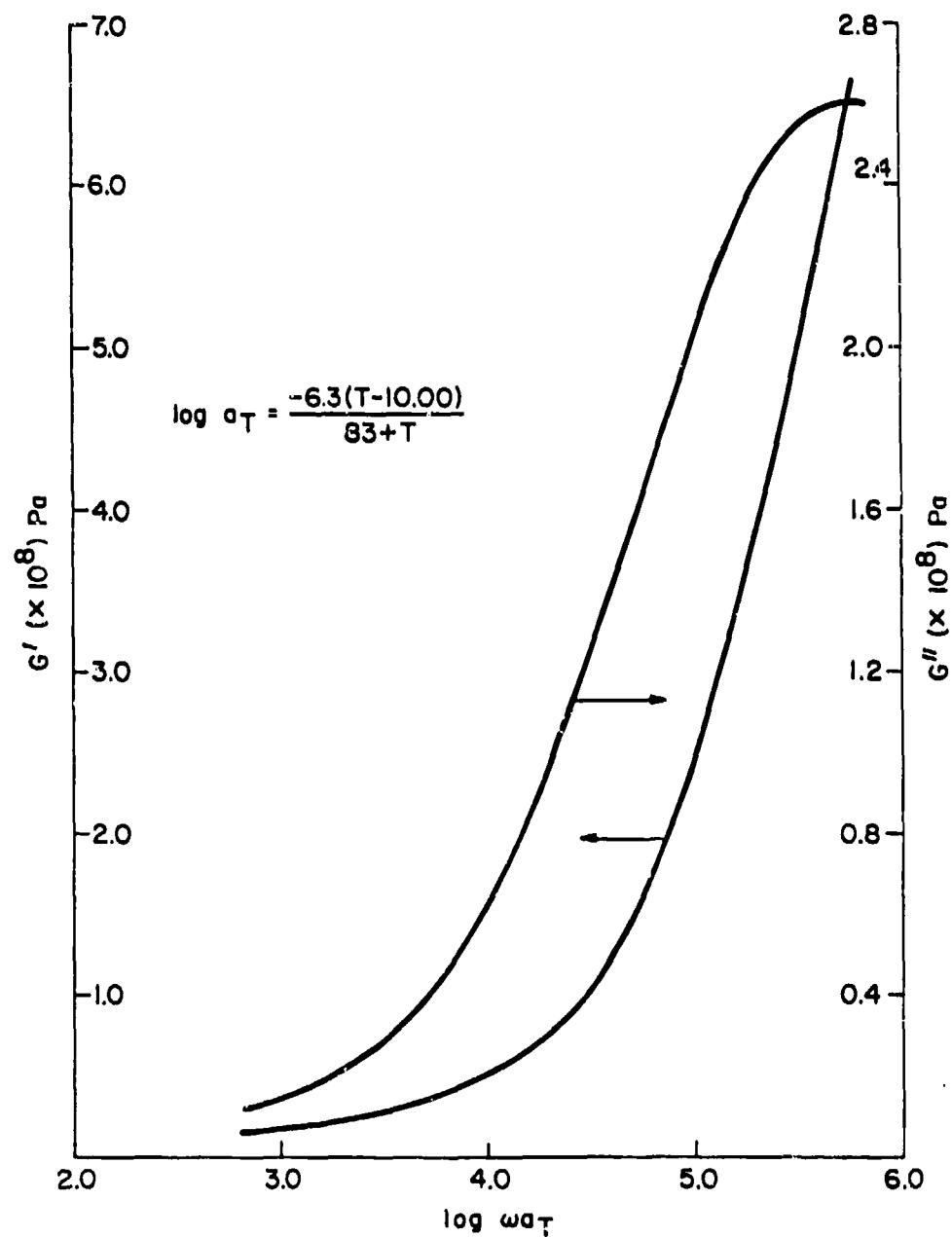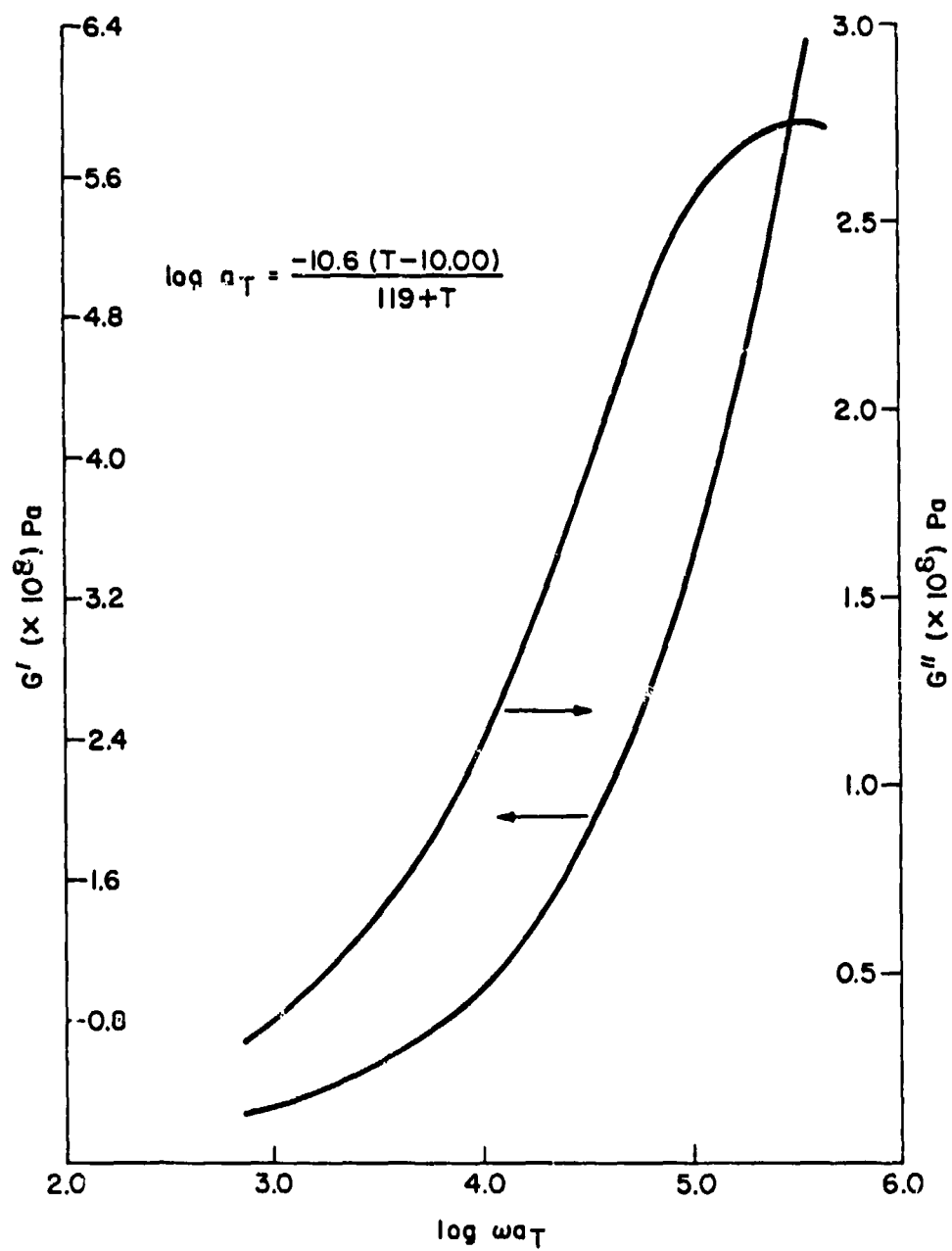
(3) Nitrile Rubber Formulation 314-1066
(Ref. 10)

$$\log a_T = \frac{-7.5\,(T-10.00)}{64+T}$$

$$\log a_T = \frac{-4.42\,(T-10.00)}{36+T}$$
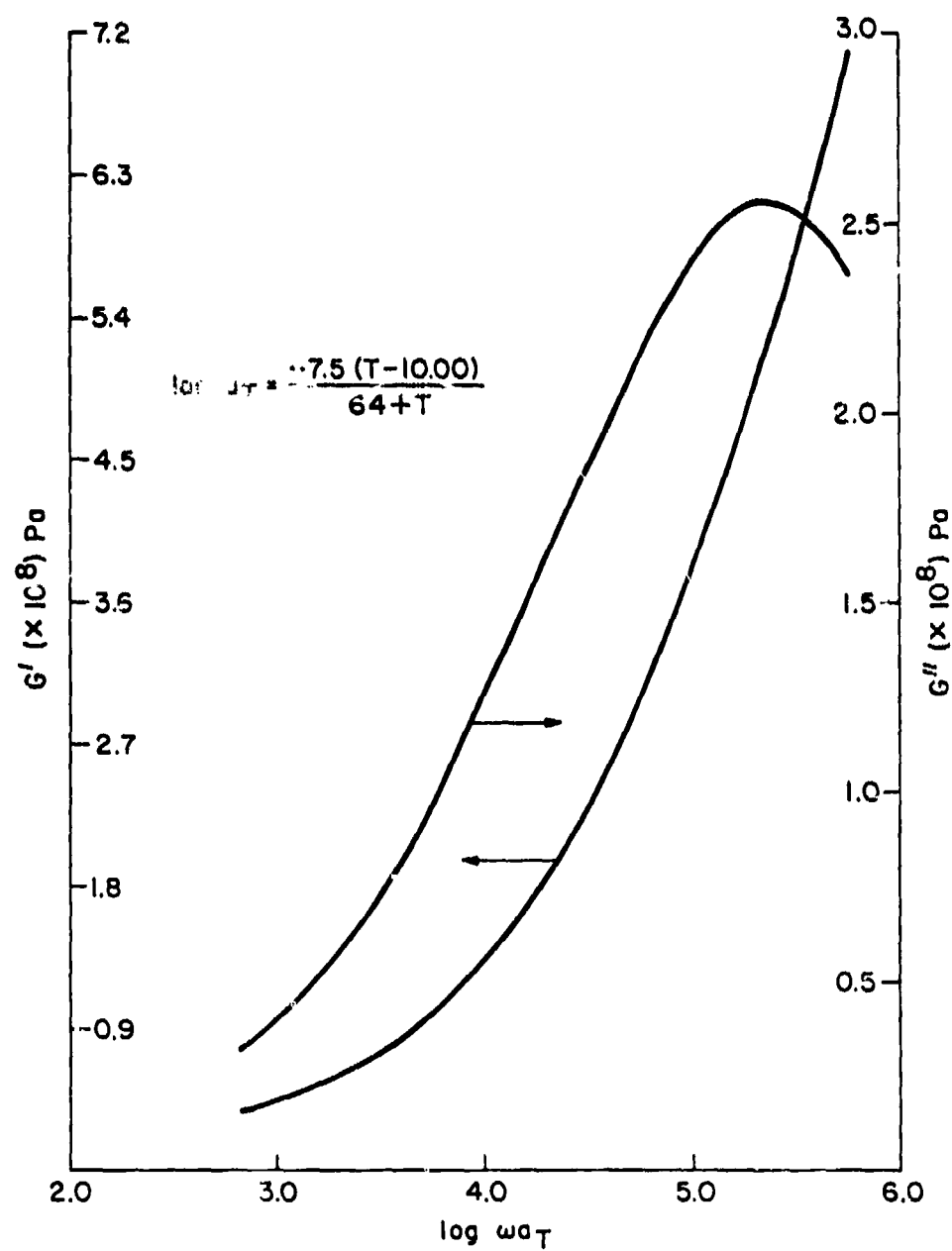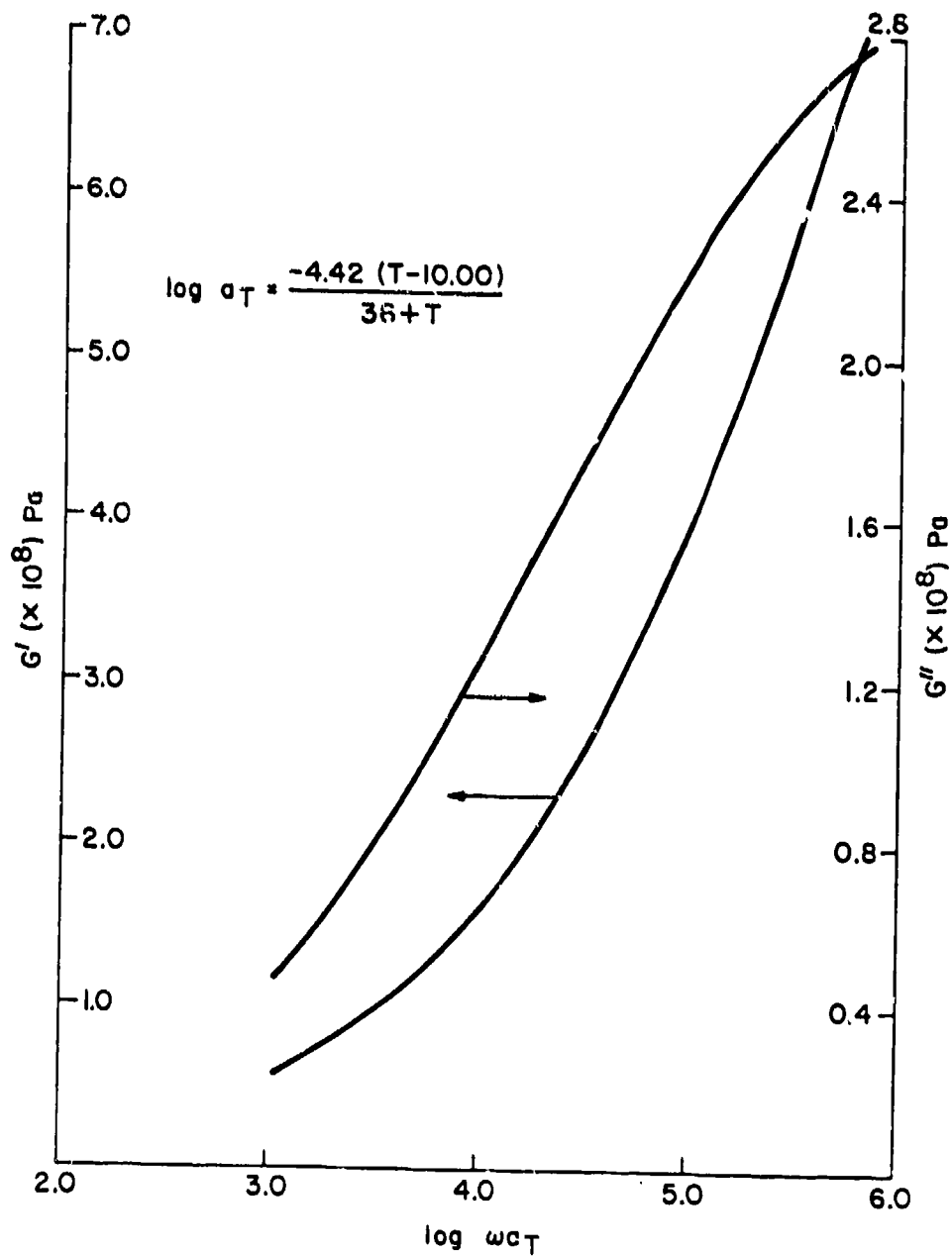
(5) Nitrile Rubber Formulation 314-1068
(Ref. 10)

$$\log a_T = \frac{-10.3\,(T-10.00)}{90-T}$$
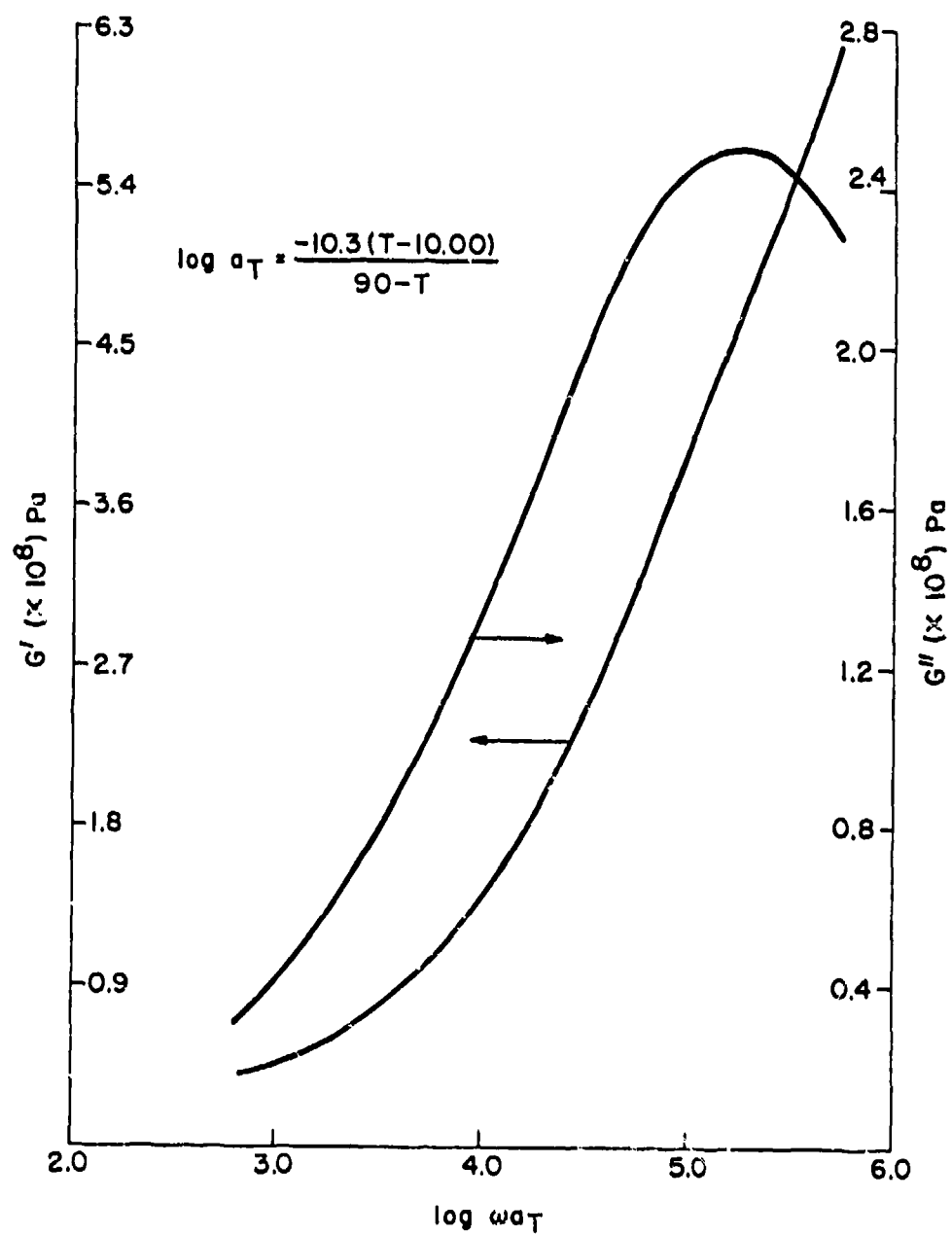
(6)   Nitrile Rubber Formulation 314-1069

(Ref. 10)

$$\log a_T = \frac{-15.5\,(T-10.00)}{150+T}$$
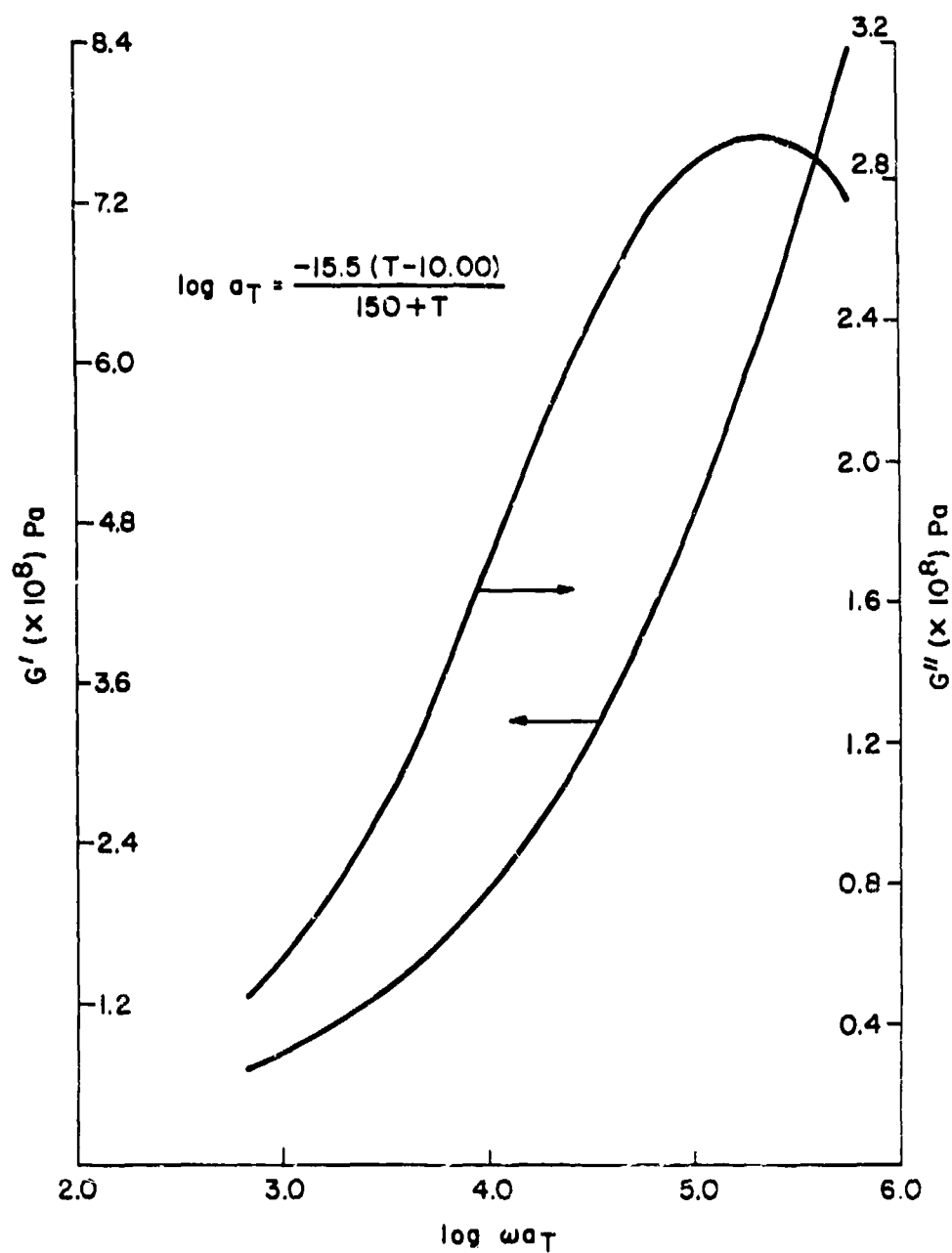
(7) Nitrile Rubber Formulation 314-1070

(Ref. 10)
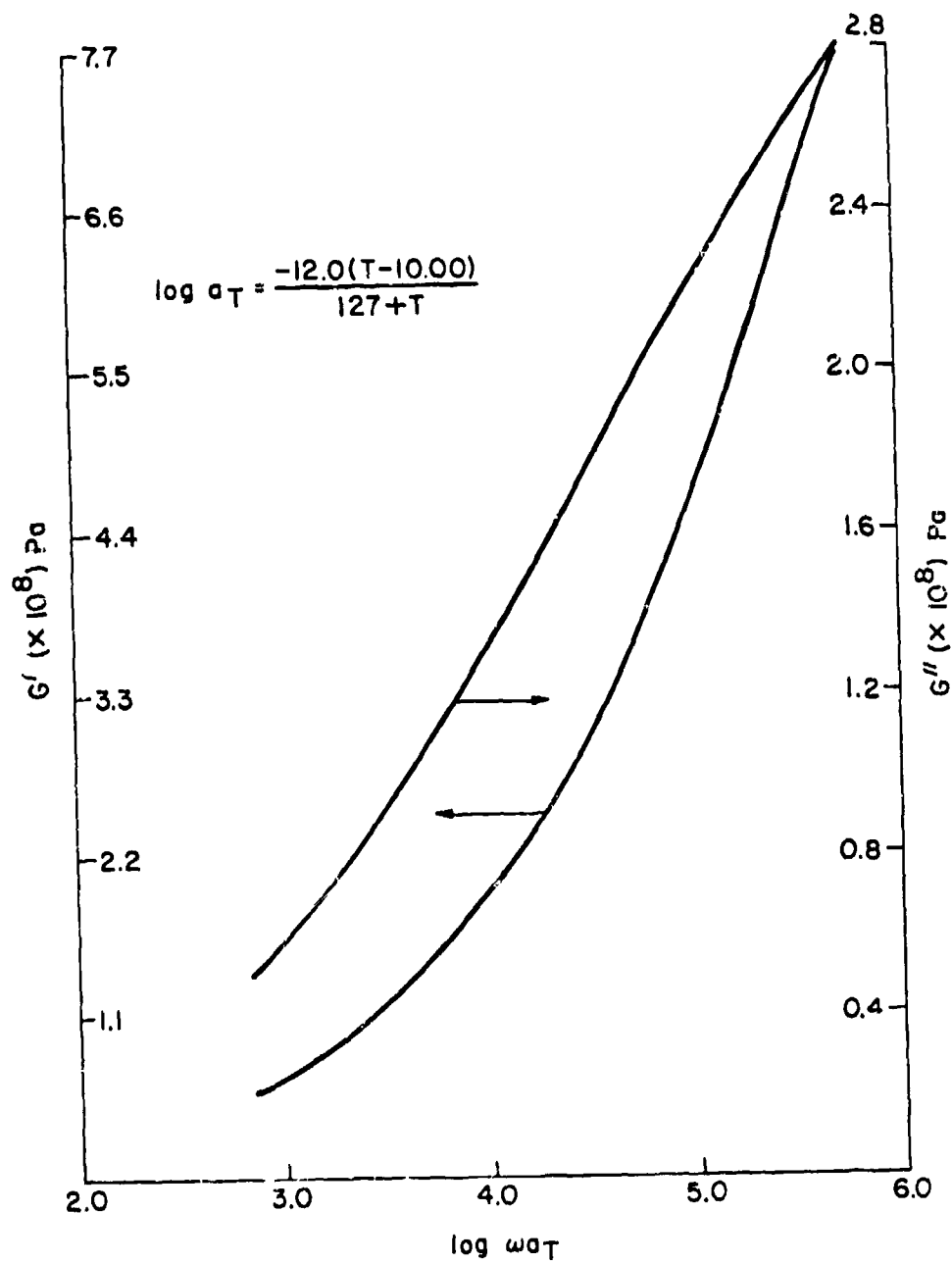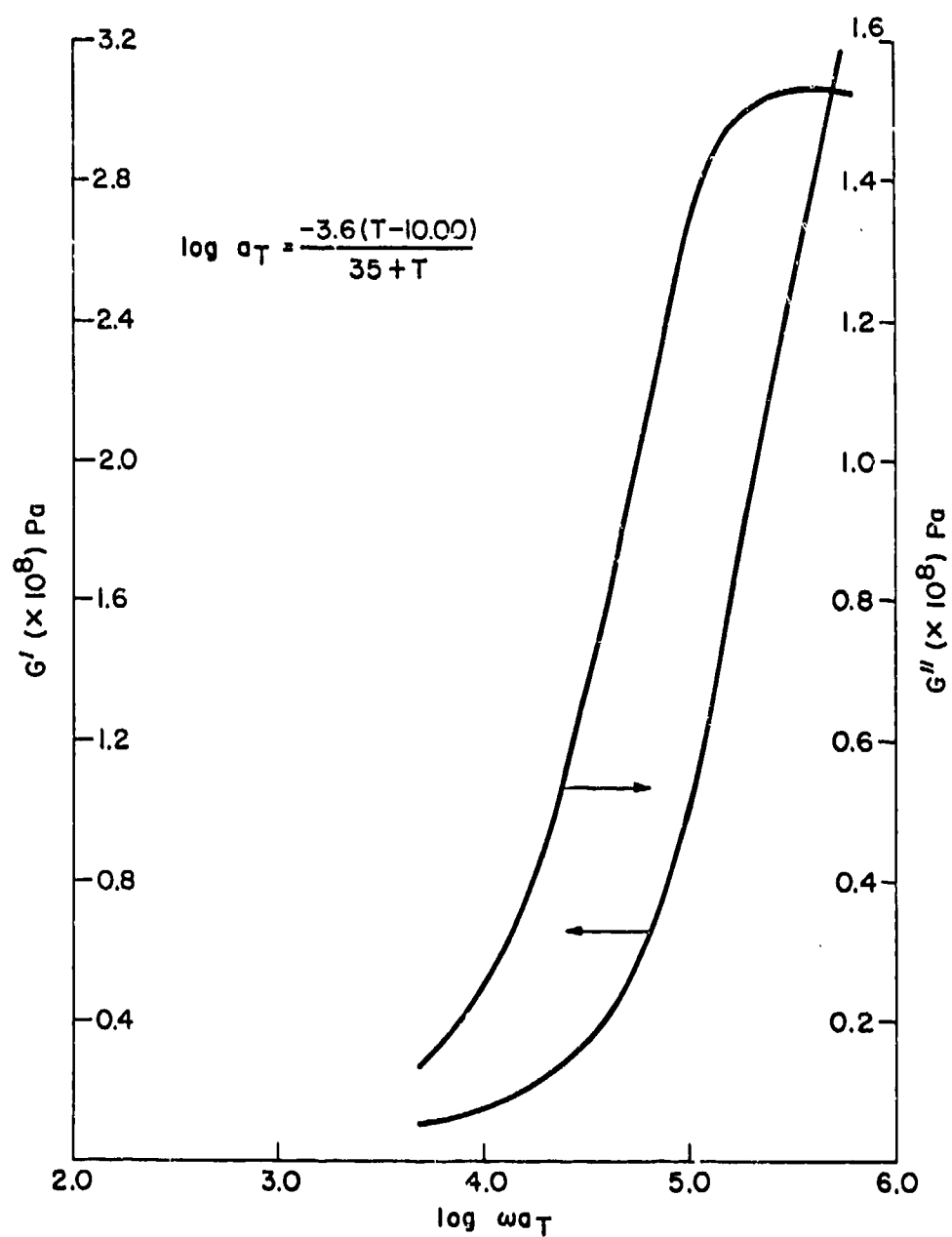
$$\log a_T = \frac{-12.0(T-10.00)}{127+T}$$

$$\log a_T = \frac{-3.6(T-10.00)}{35+T}$$

$$\log a_T = \frac{-9.8\,(T-10.00)}{109+T}$$

$$\log a_T = \frac{-10.5(T-10.00)}{75+T}$$
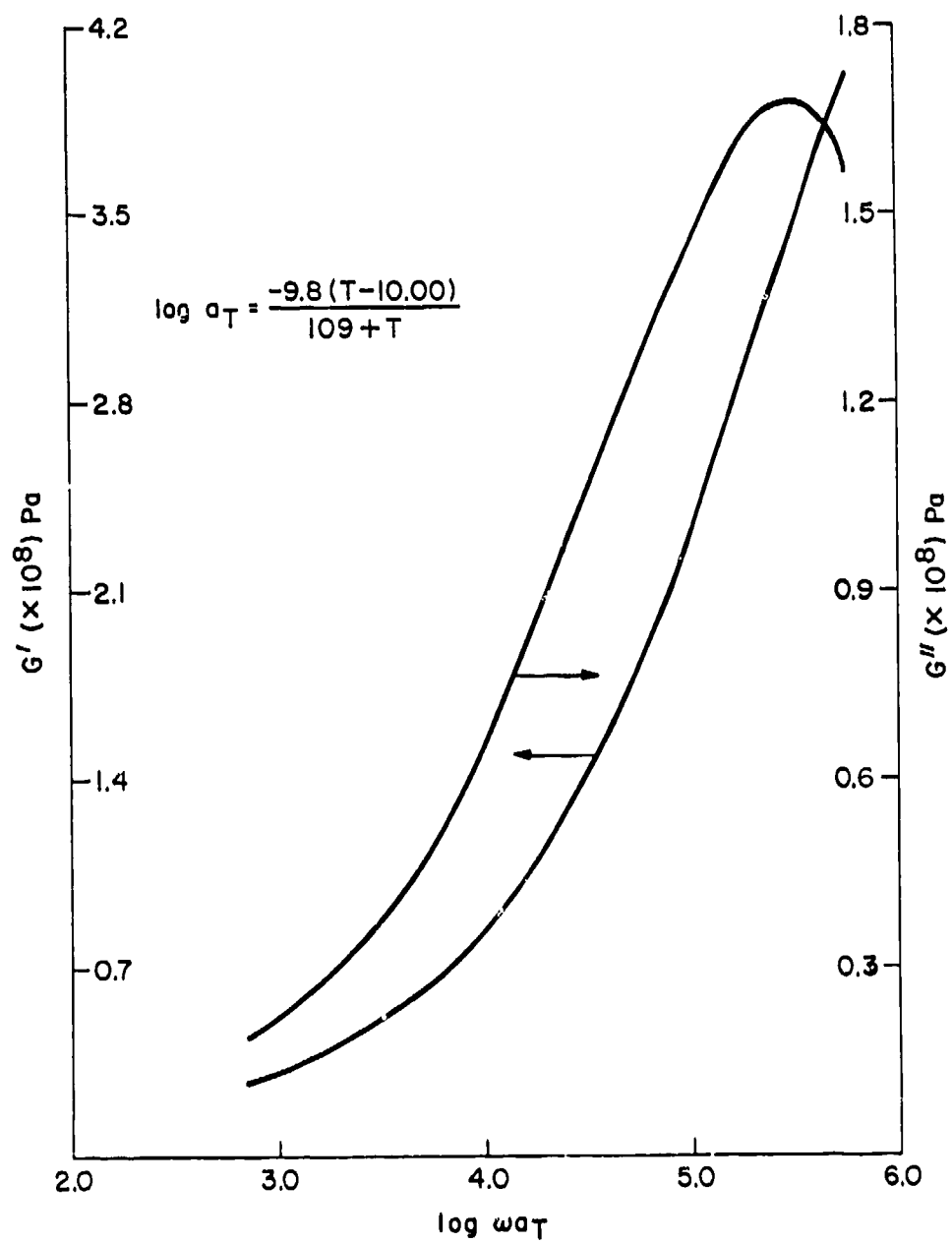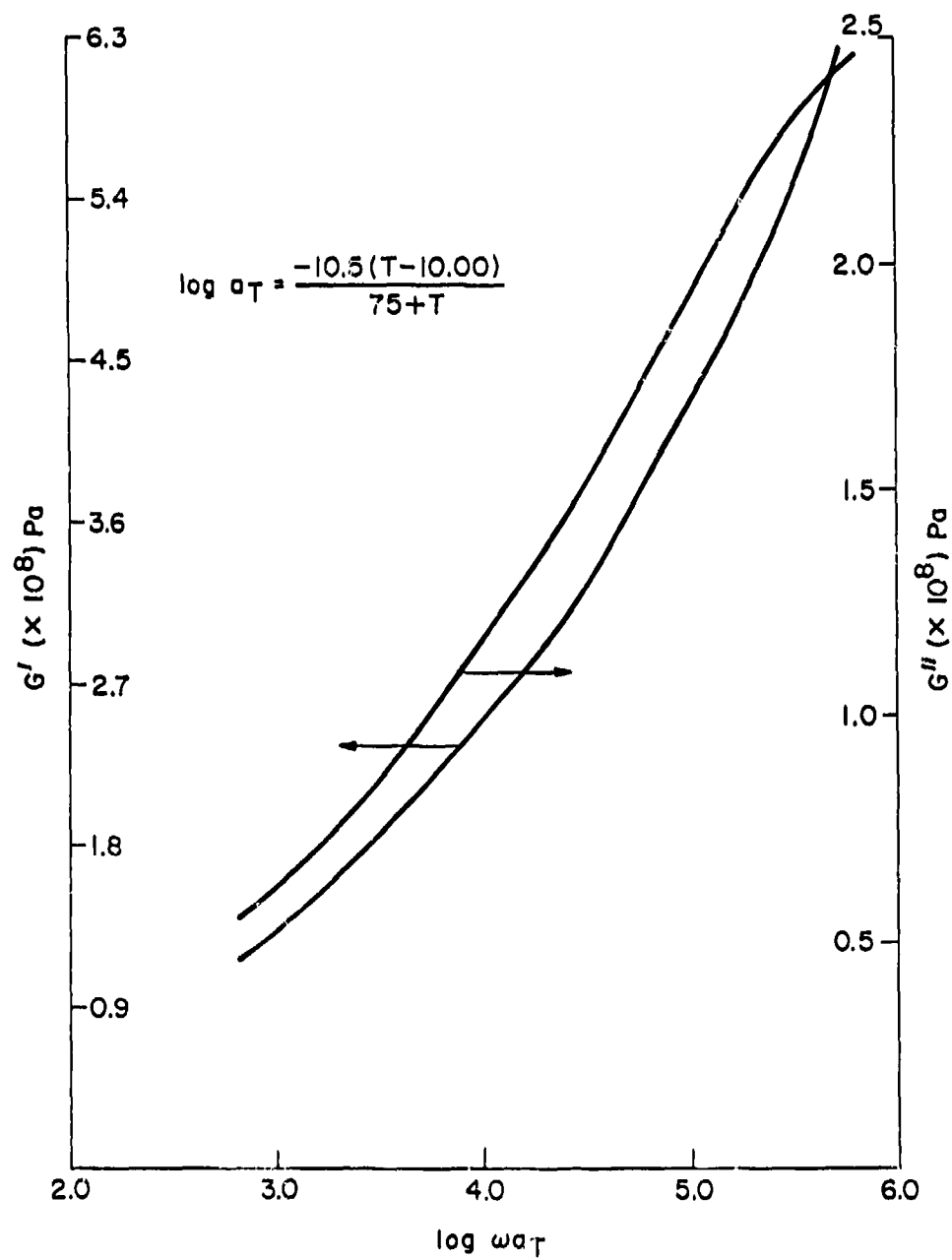
(11)   Nitrile Rubber Formulation 314-1077
(Ref. 10)

$$\log a_T = \frac{-6.72(T-10.00)}{72+T}$$
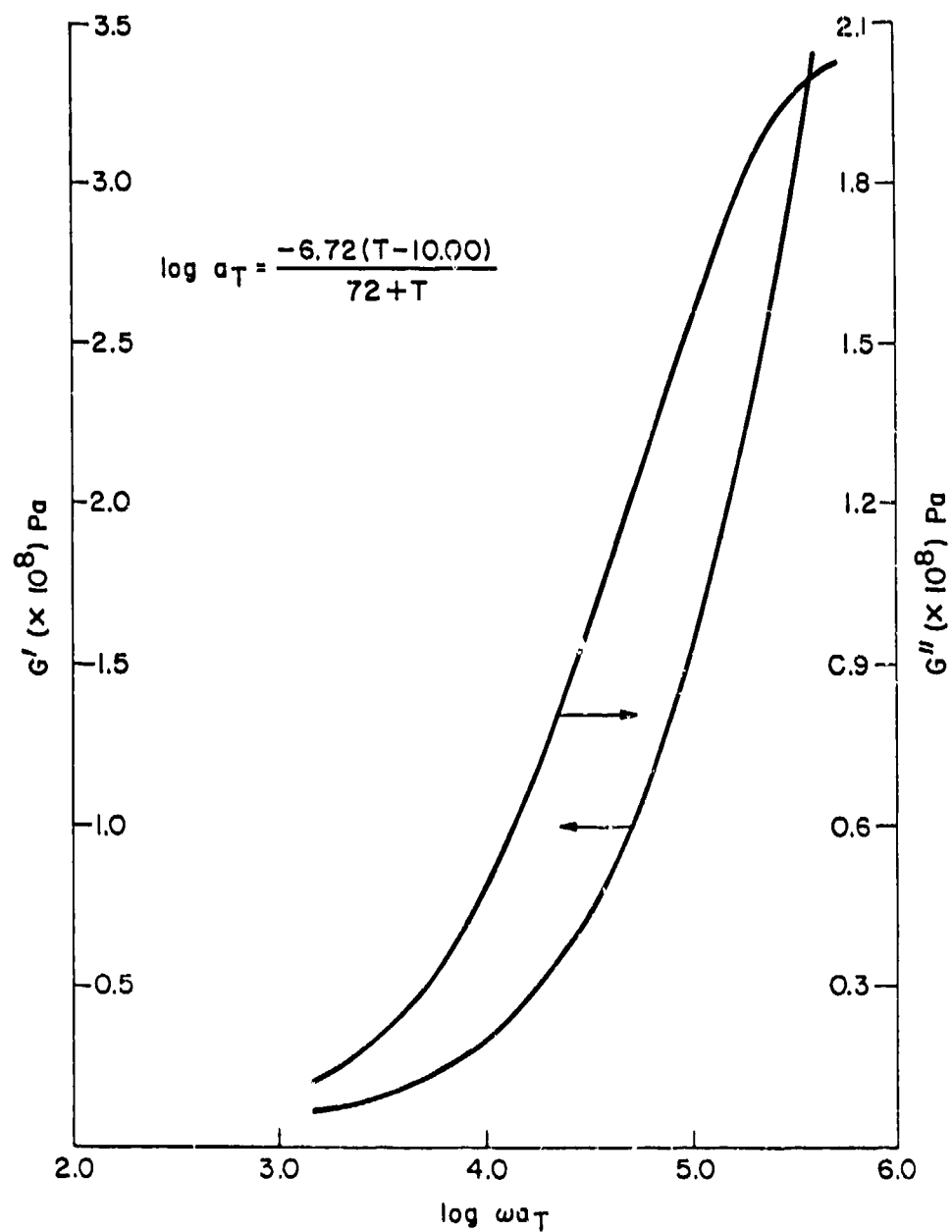
(12)   Nitrile Rubber Formulation 314-1078

(Ref. 10)
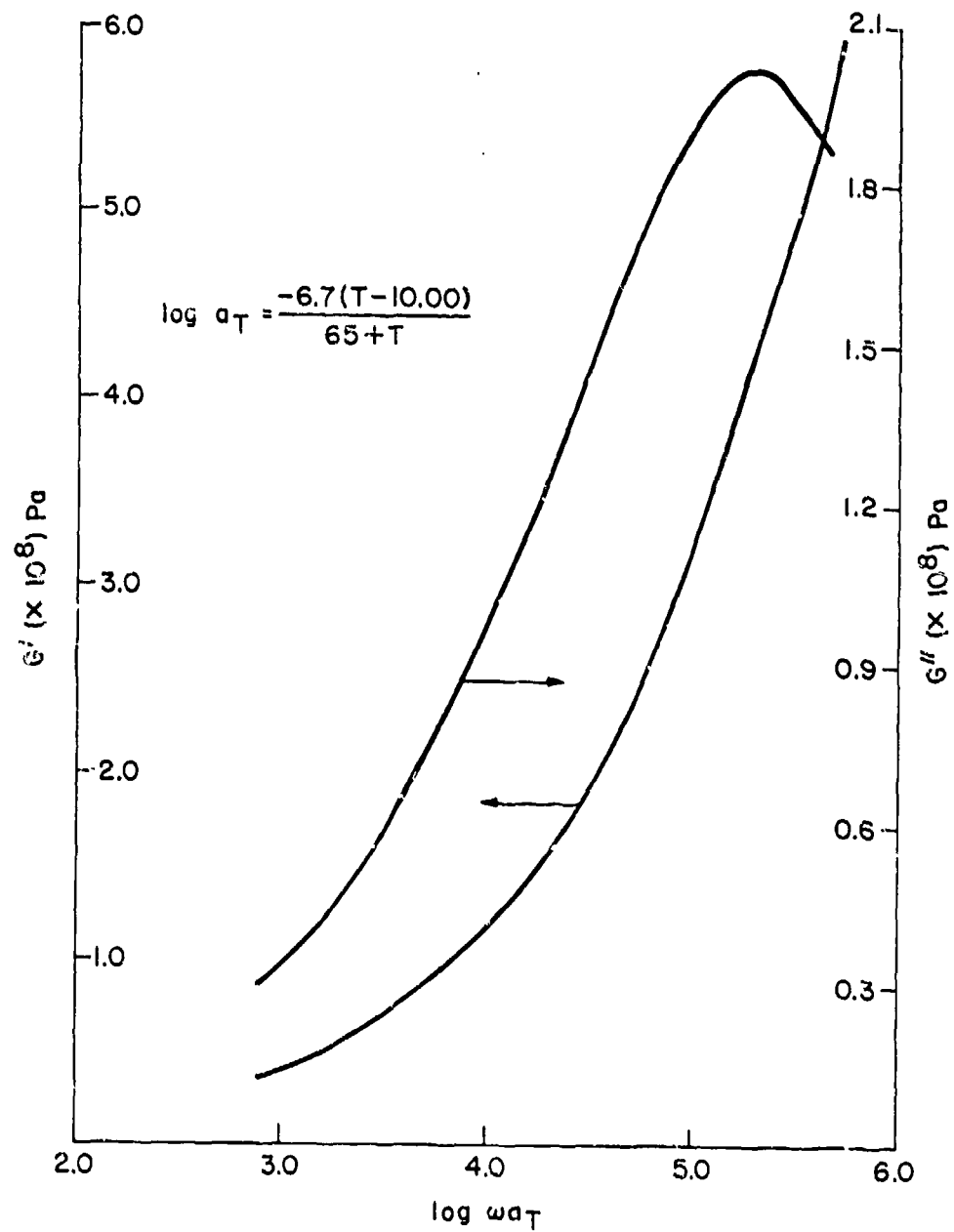
$$\log a_T = \frac{-6.7(T-10.00)}{65+T}$$

$$\log a_T = \frac{-4.00(T-10.00)}{21+T}$$

$$\log a_T = \frac{-14.9(T-10.00)}{121+T}$$

Figure axes: G' ($\times 10^8$) Pa (left), G'' ($\times 10^8$) Pa (right), log ωa_T (horizontal)
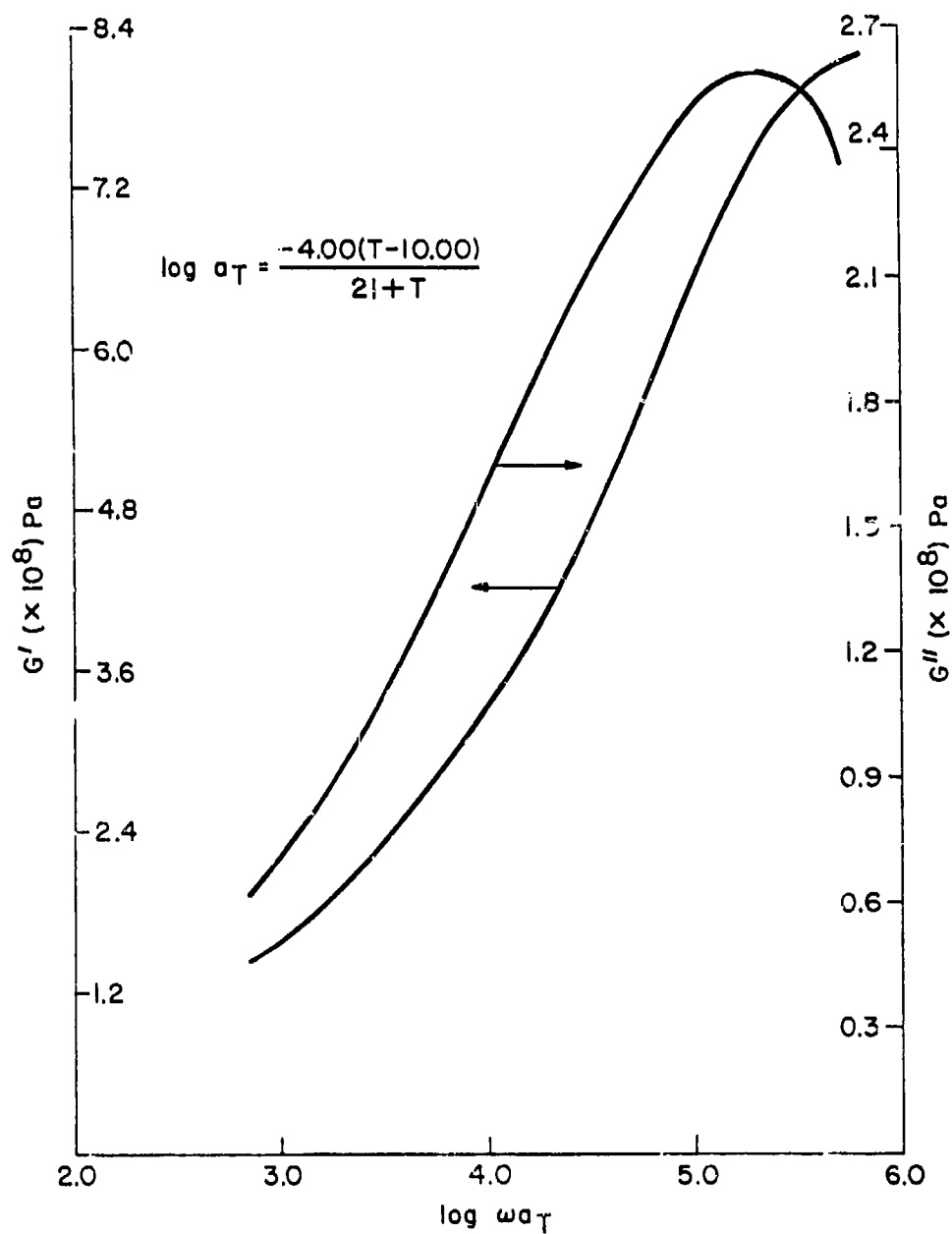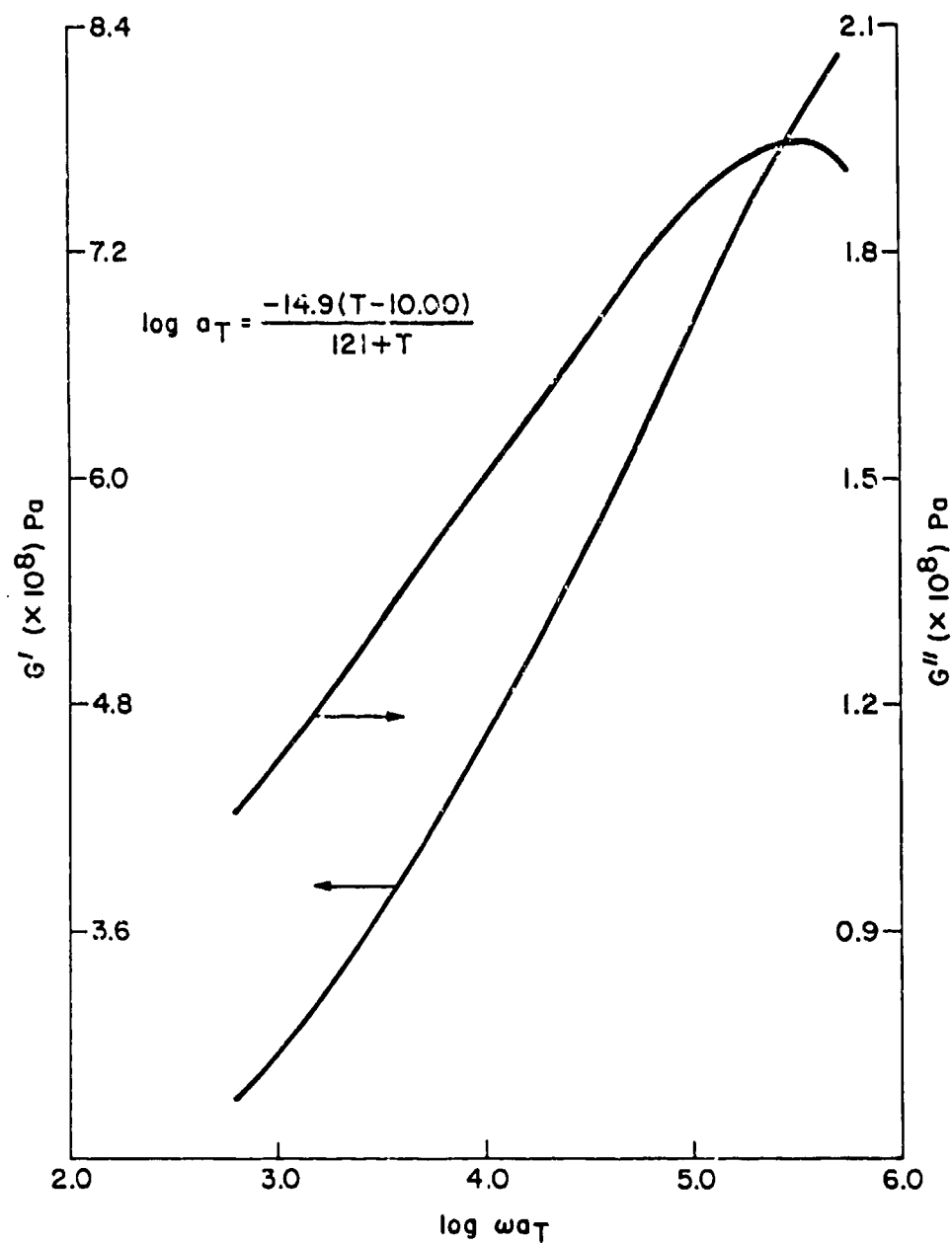
e. *Nitrile Rubber Formulations* 1474, 1476–81, 1489, 1492, *and* 1507–09

(1) Nitrile Rubber Formulation 1474
(Ref. 10)

$$\log a_T = \frac{-5.1(T-10.00)}{49+T}$$
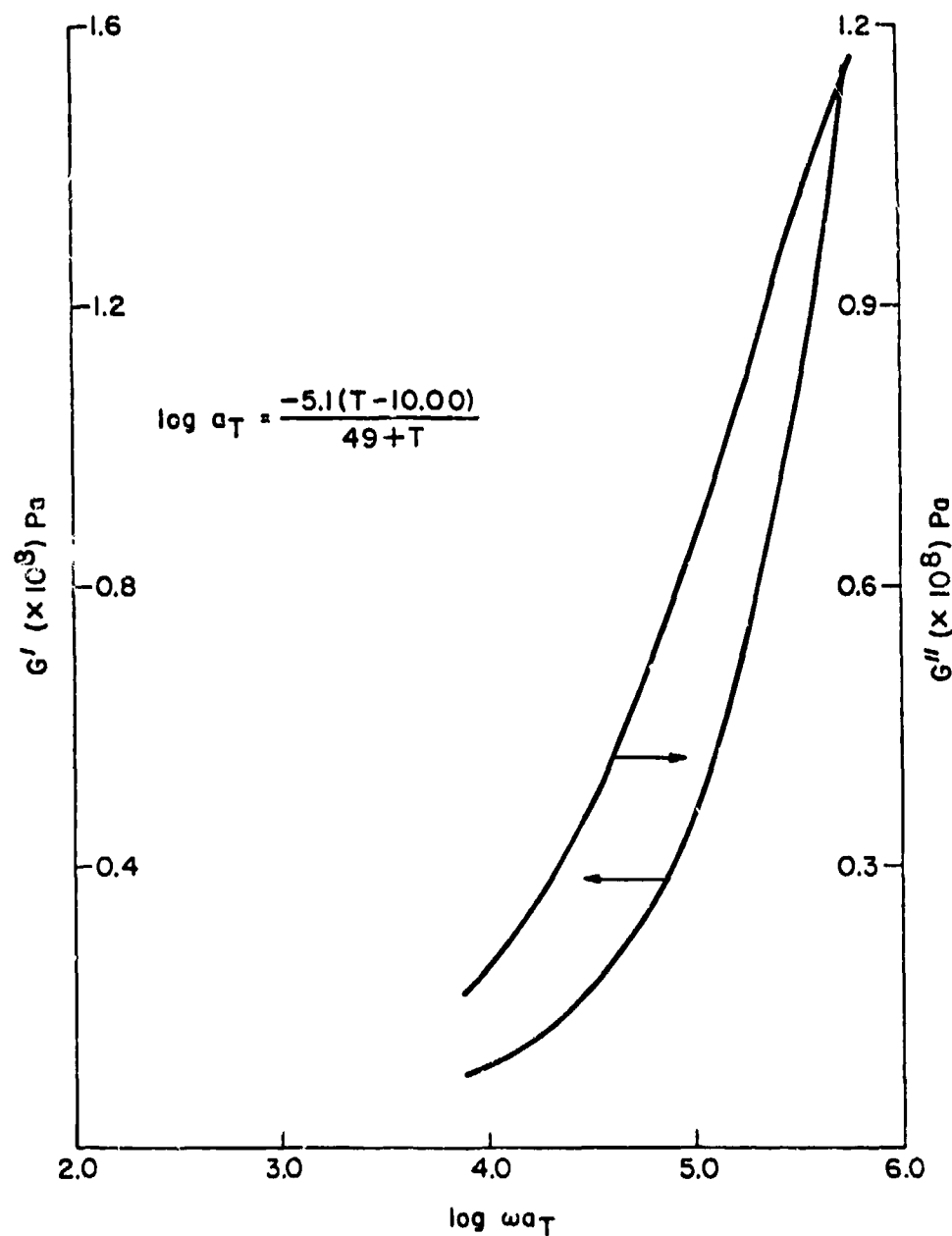
(2)   Nitrile Rubber Formulation 1476
                                    (Ref. 10)

$$\log a_T = \frac{-21(T-10.00)}{231+T}$$
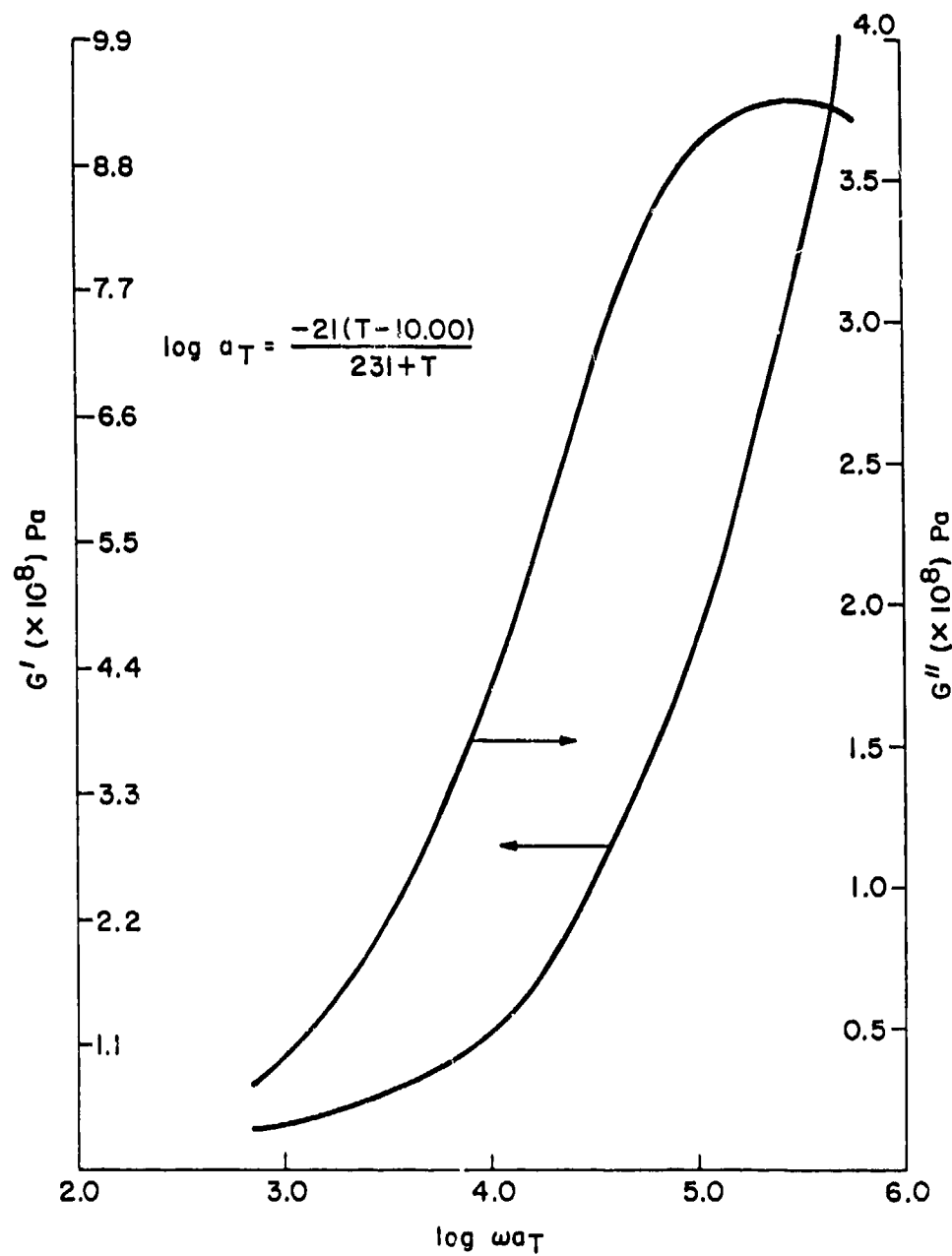
(3)   Nitrile Rubber Formulation 1477
                                     (Ref. 10)

$$\log a_T = \frac{-12.1\,(T-115.00)}{105+T}$$
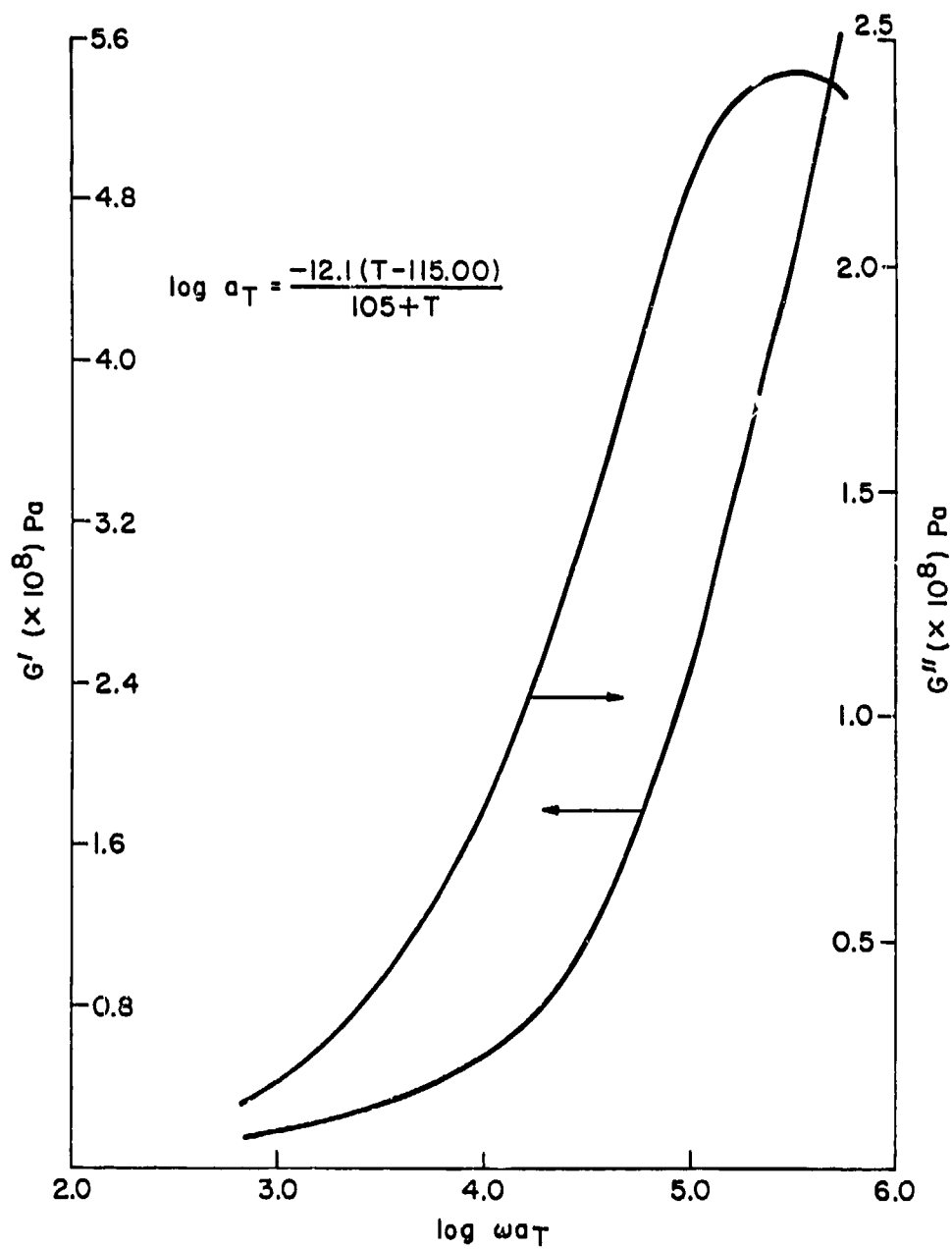
(4) Nitrile Rubber Formulation 1478
(Ref. 10)

$$\log a_T = \frac{-16.9(T-10.00)}{170+T}$$
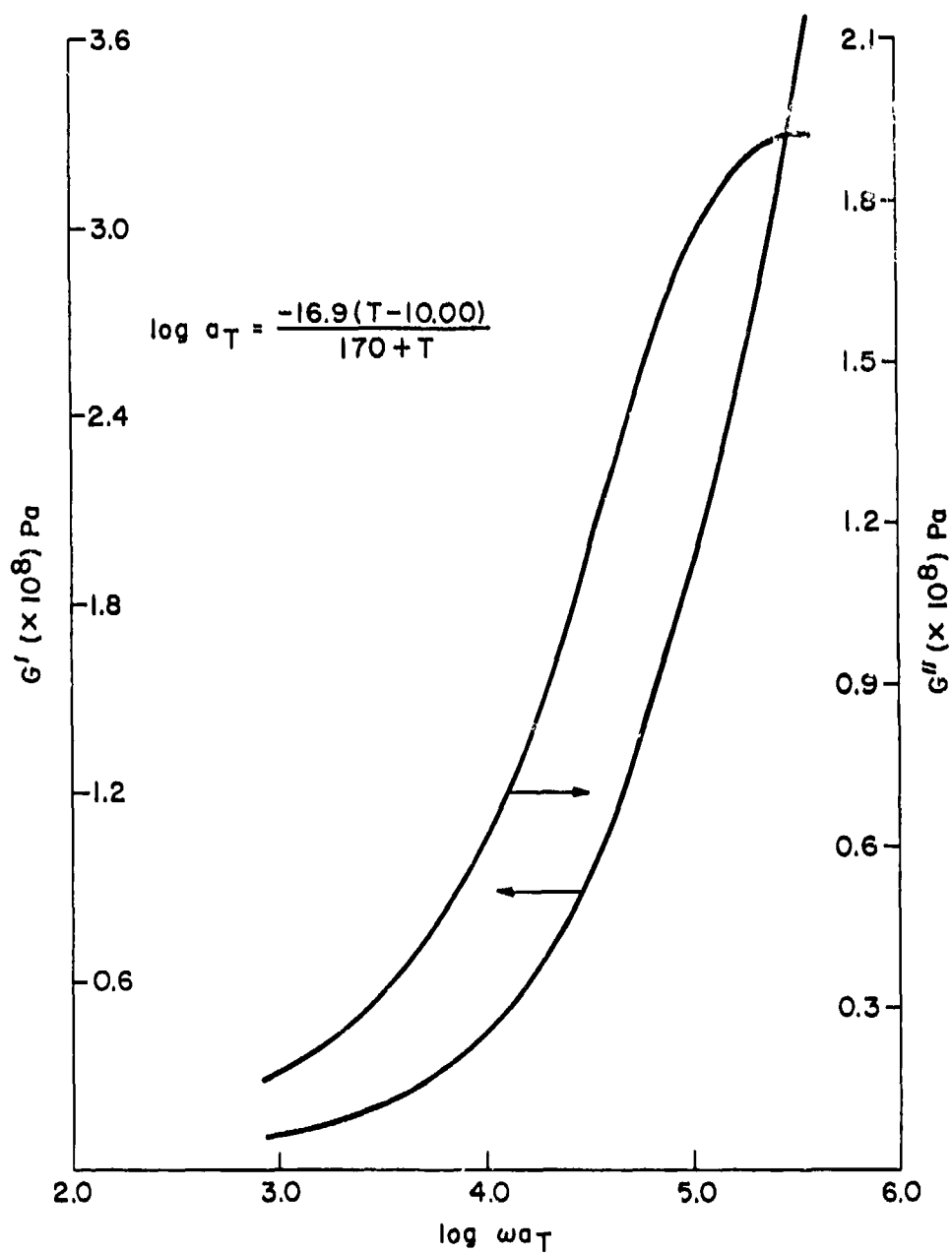
(5) Nitrile Rubber Formulation 1479
(Ref. 10)

$$\log a_T = \frac{-12.9(T-10.00)}{107+T}$$
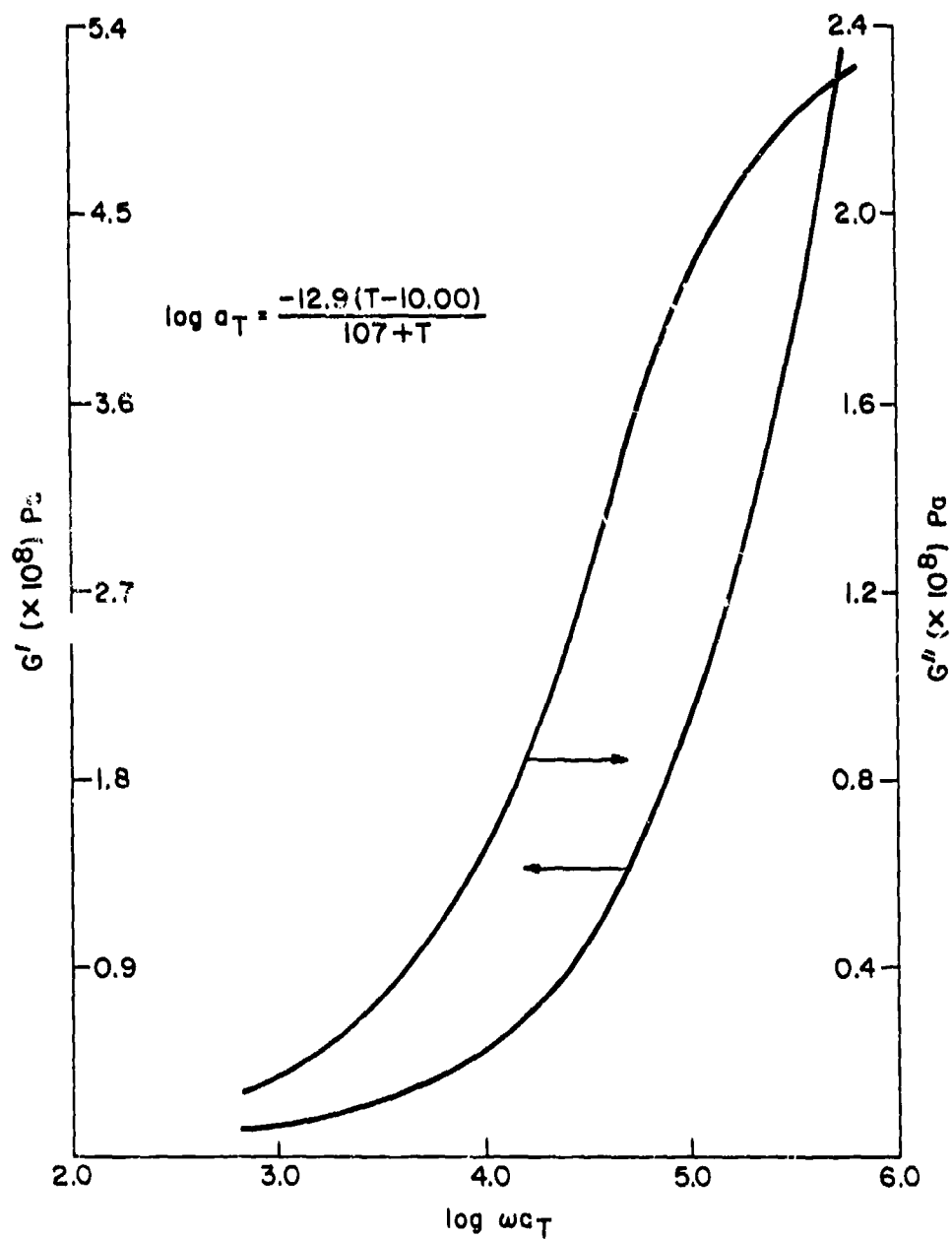
(6)   Nitrile Rubber Formulation 1480
(Ref. 10)

$$\log a_T = \frac{-2.8(T-10.00)}{22+T}$$
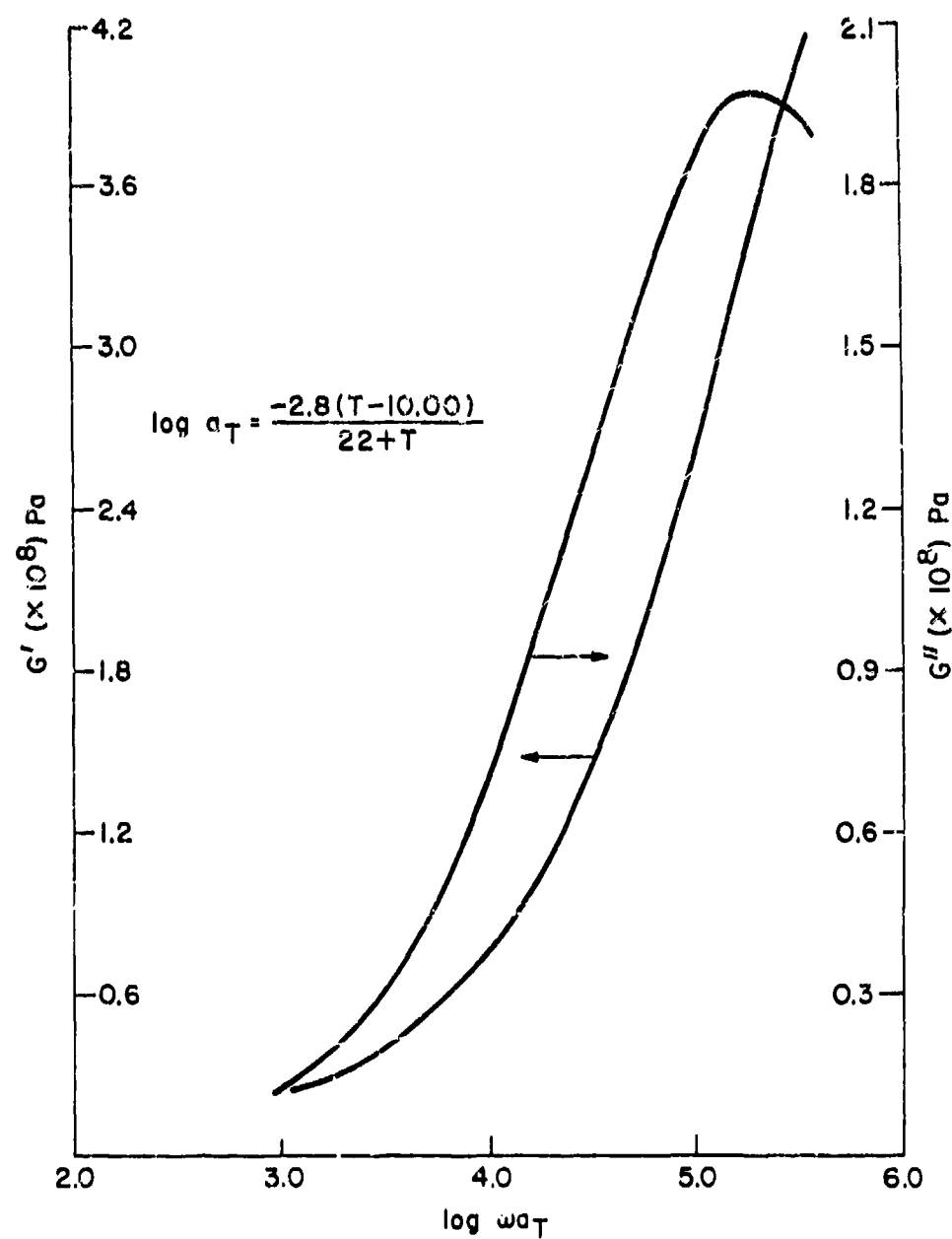
(7)   Nitrile Rubber Formulation 1481
                                  (Ref. 10)

$$\log a_T = \frac{-15.2(T-10.00)}{150+T}$$
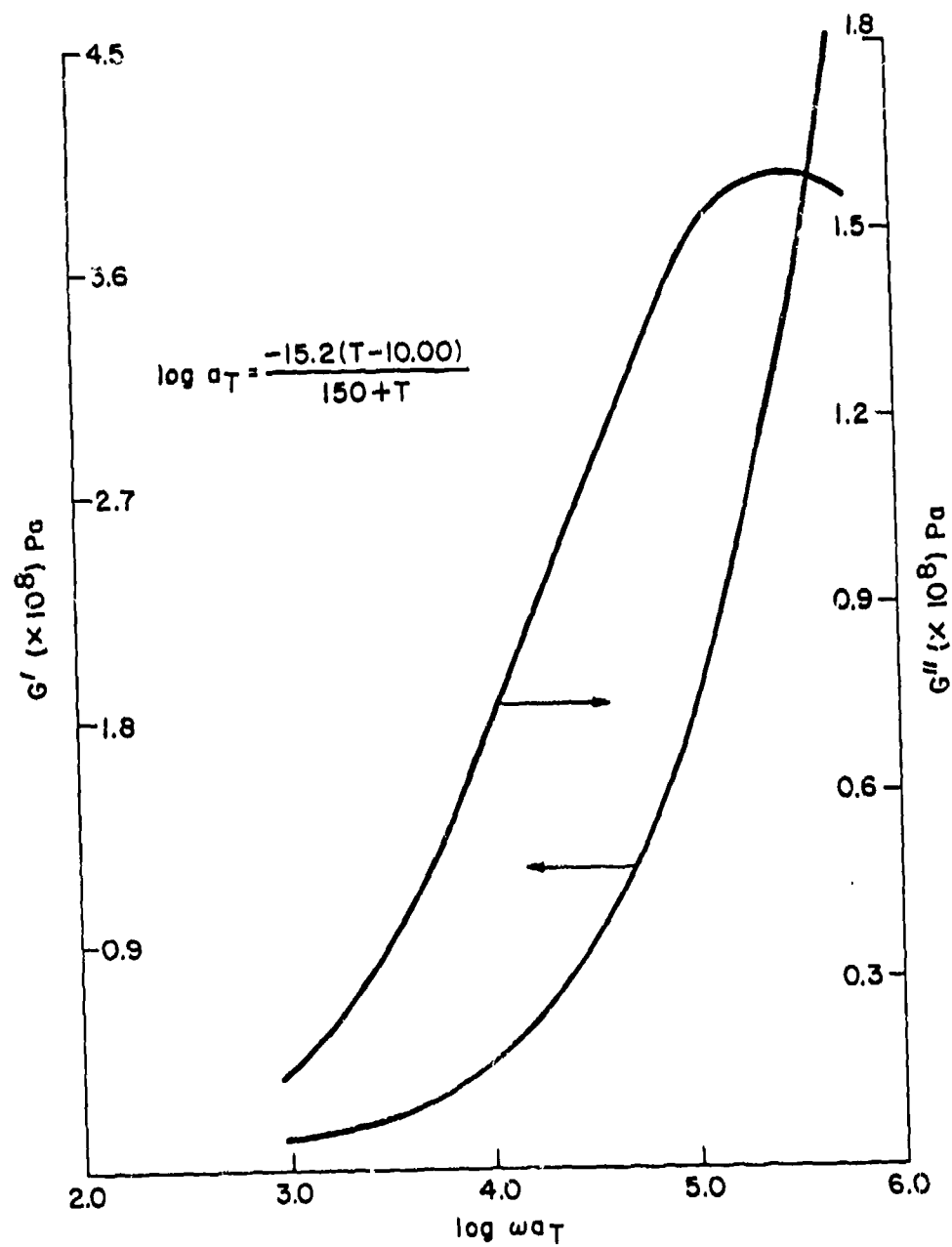
(8)   Nitrile Rubber Formulation 1489
(Ref. 10)

$$\log a_T = \frac{-32.2(T-10.00)}{260+T}$$
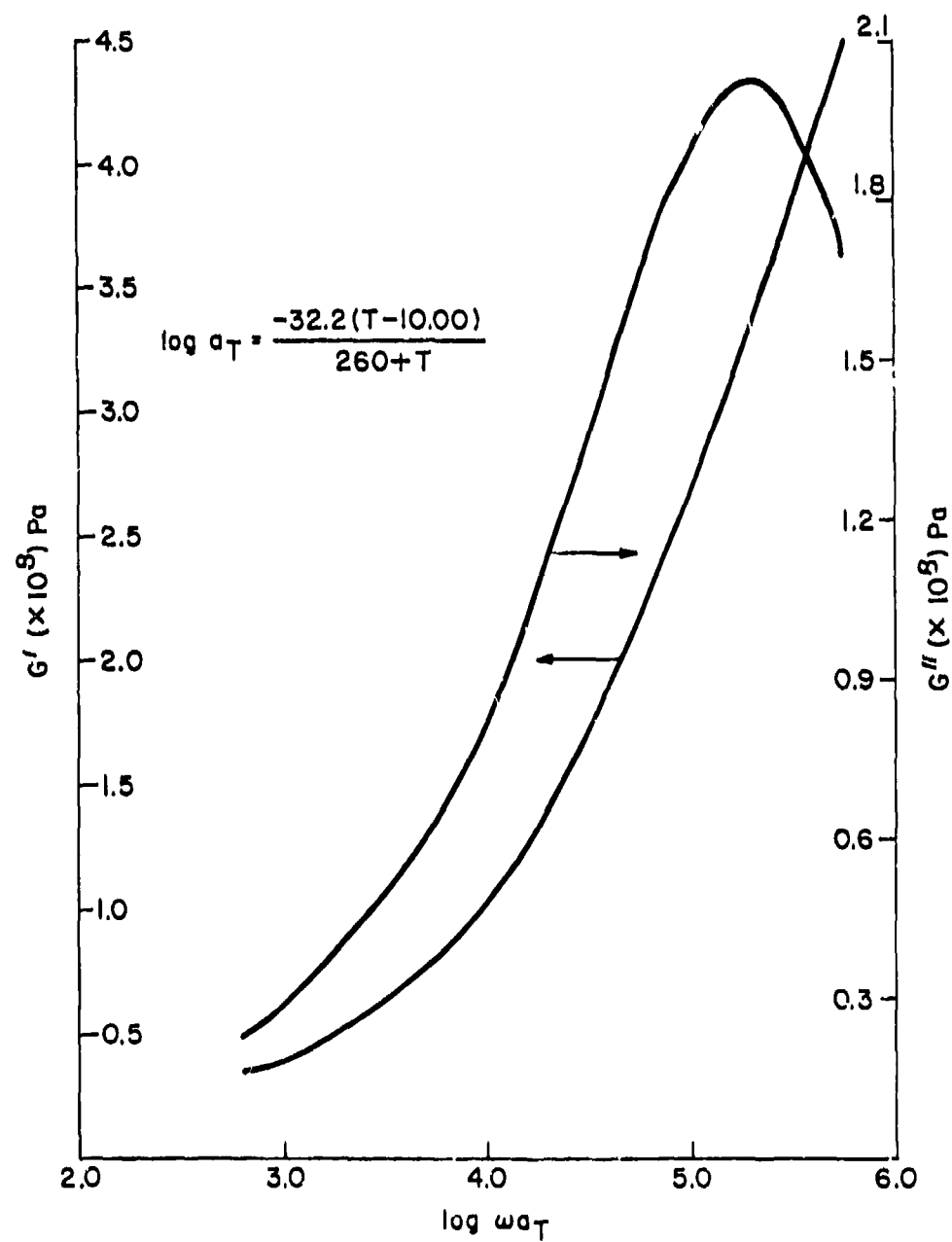
(9)   Nitrile Rubber Formulation 1492
(Ref. 10)

$$\log a_T = \frac{-11.4(T-10.00)}{106+T}$$
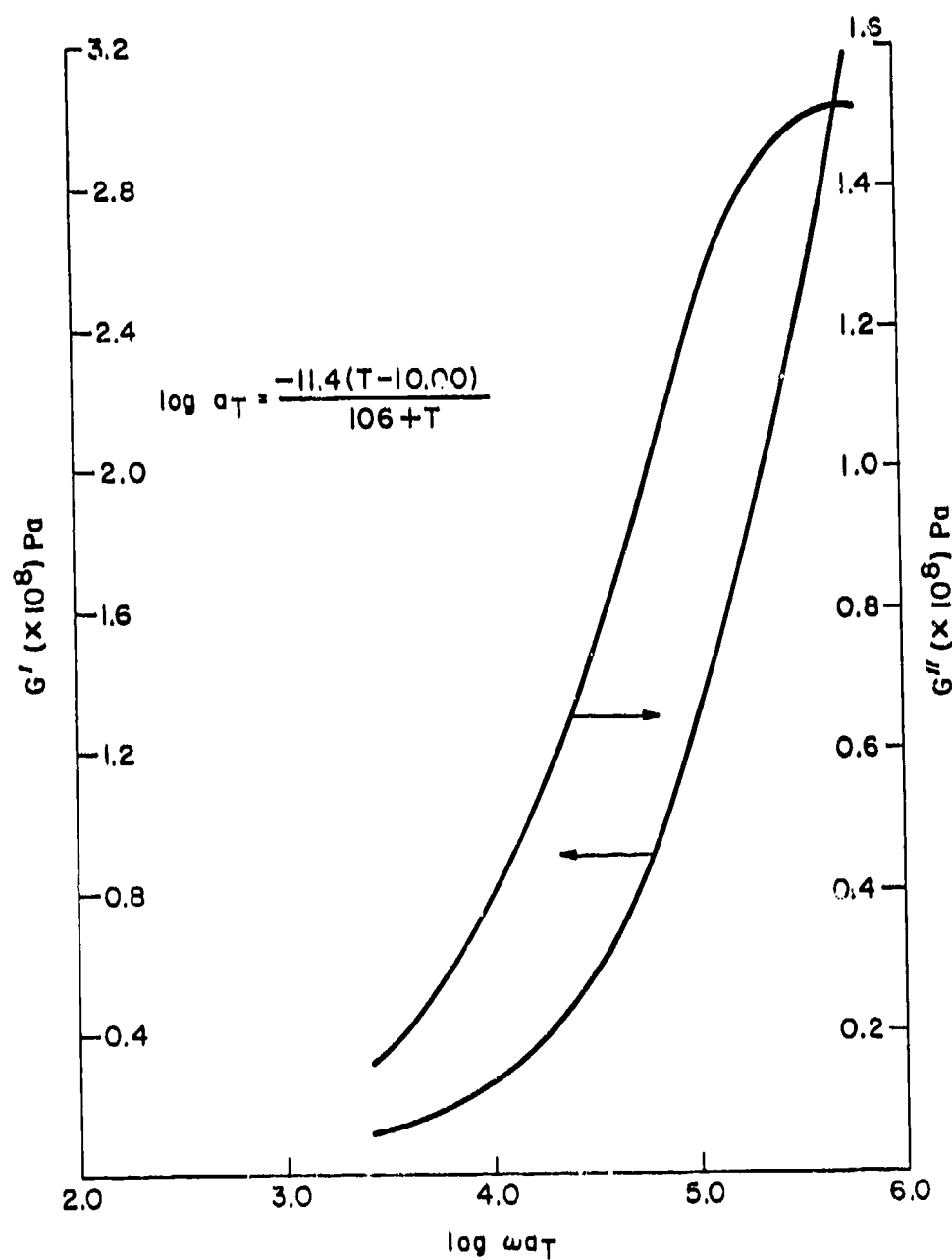
(10)   Nitrile Rubber Formulation 1507
(Ref. 10)

$$\log a_T = \frac{-8.3\,(T-10.00)}{73+T}$$

$$\log a_T = \frac{-3.7\,(T-10.00)}{30+T}$$
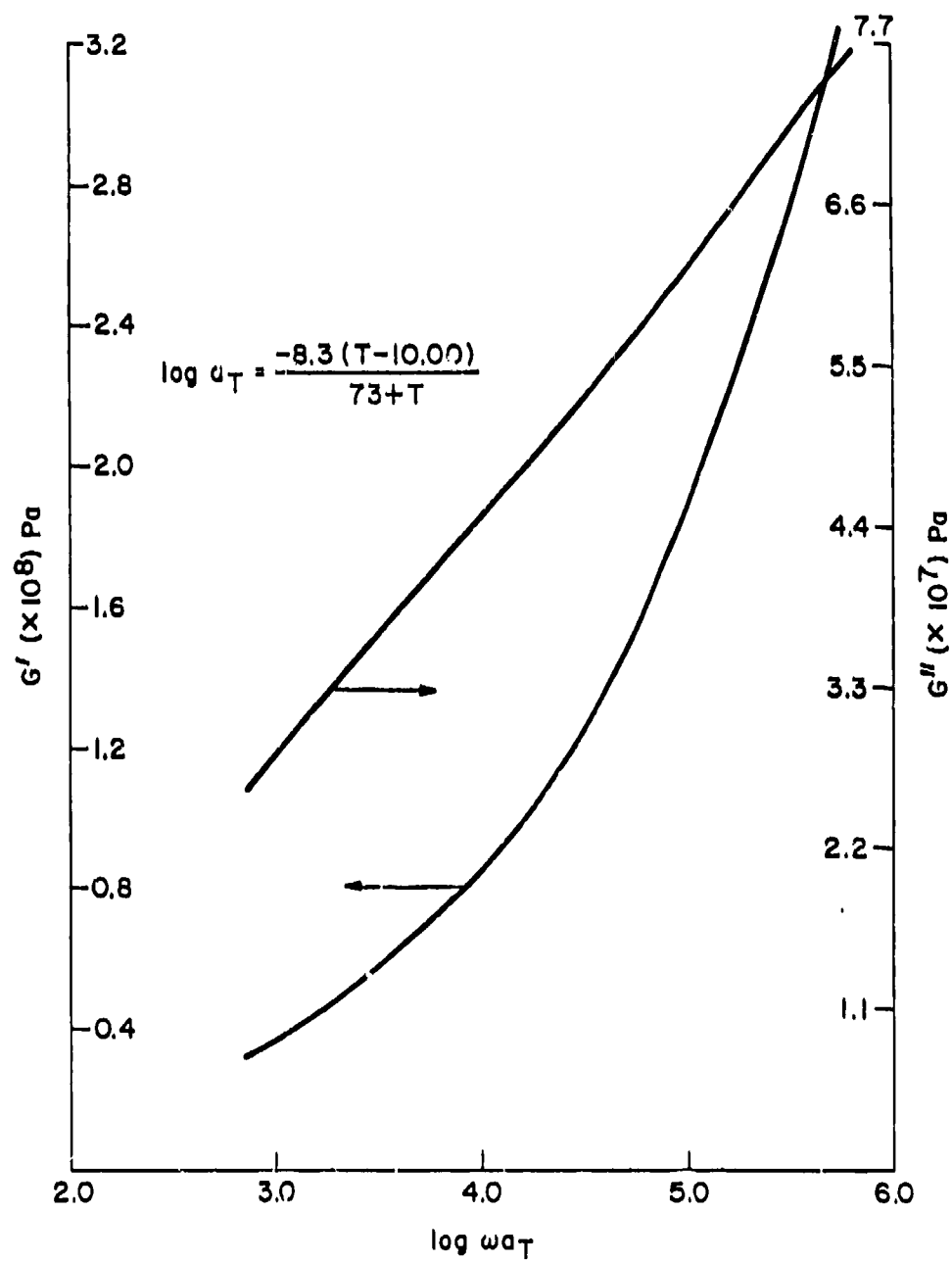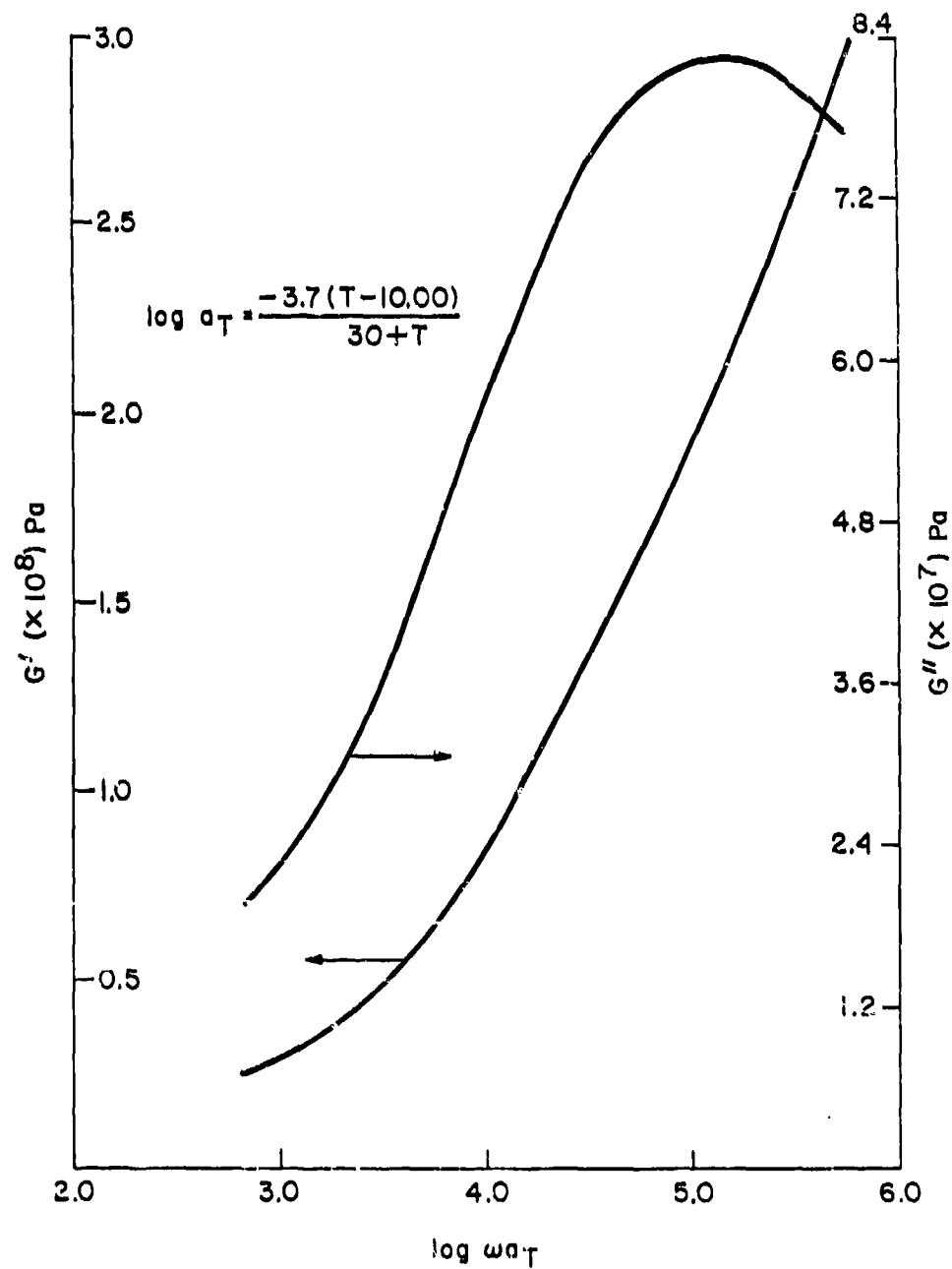
(12)   Nitrile Rubber Formulation 1509
                                                (Ref. 10)

$$\log a_T = \frac{-21.8 (T-10.00)}{125+T}$$
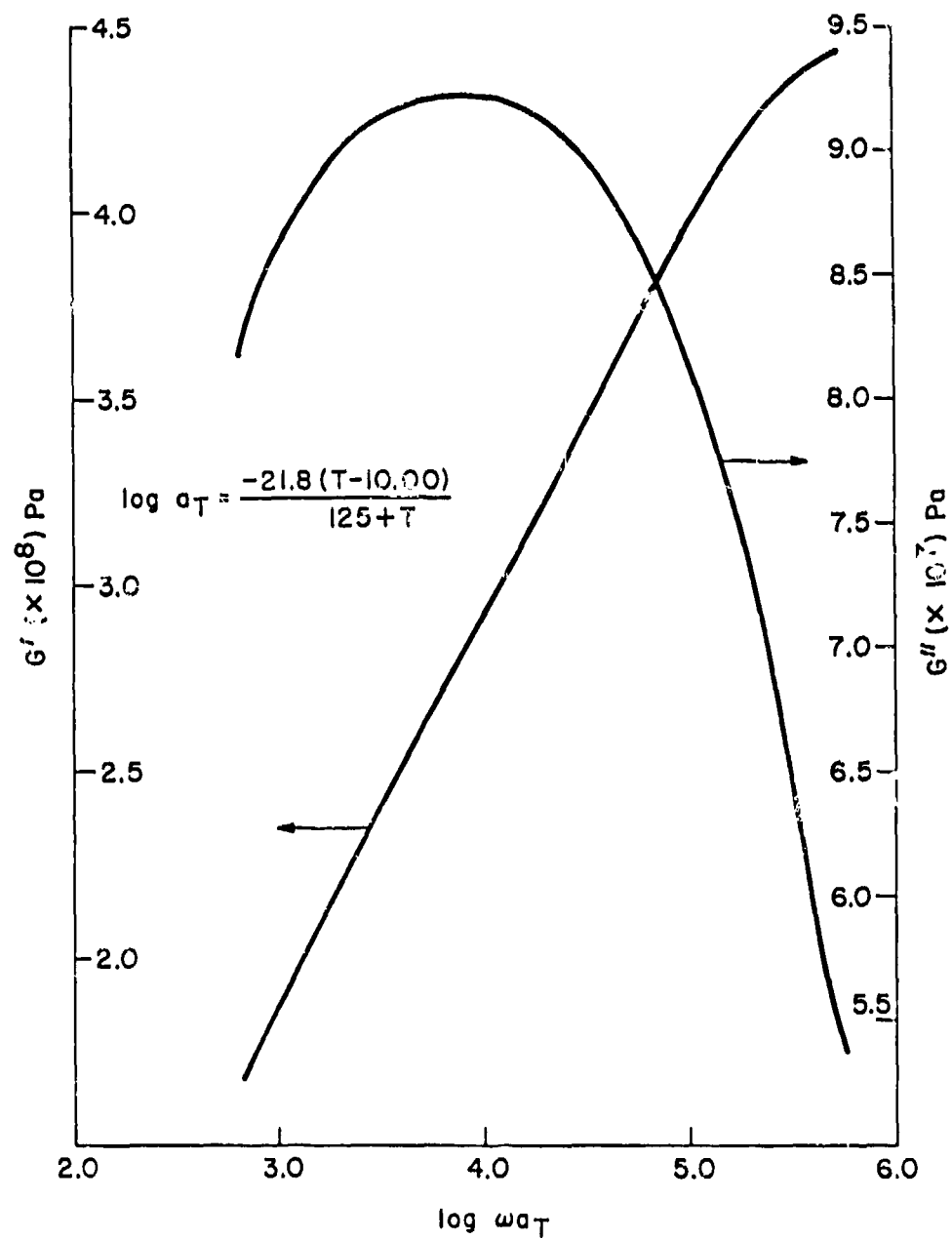
f. *Nitrile Formulation* NA 440 (Ref. 10)

$$\log a_T = \frac{-10.1(T-10.00)}{113+T}$$
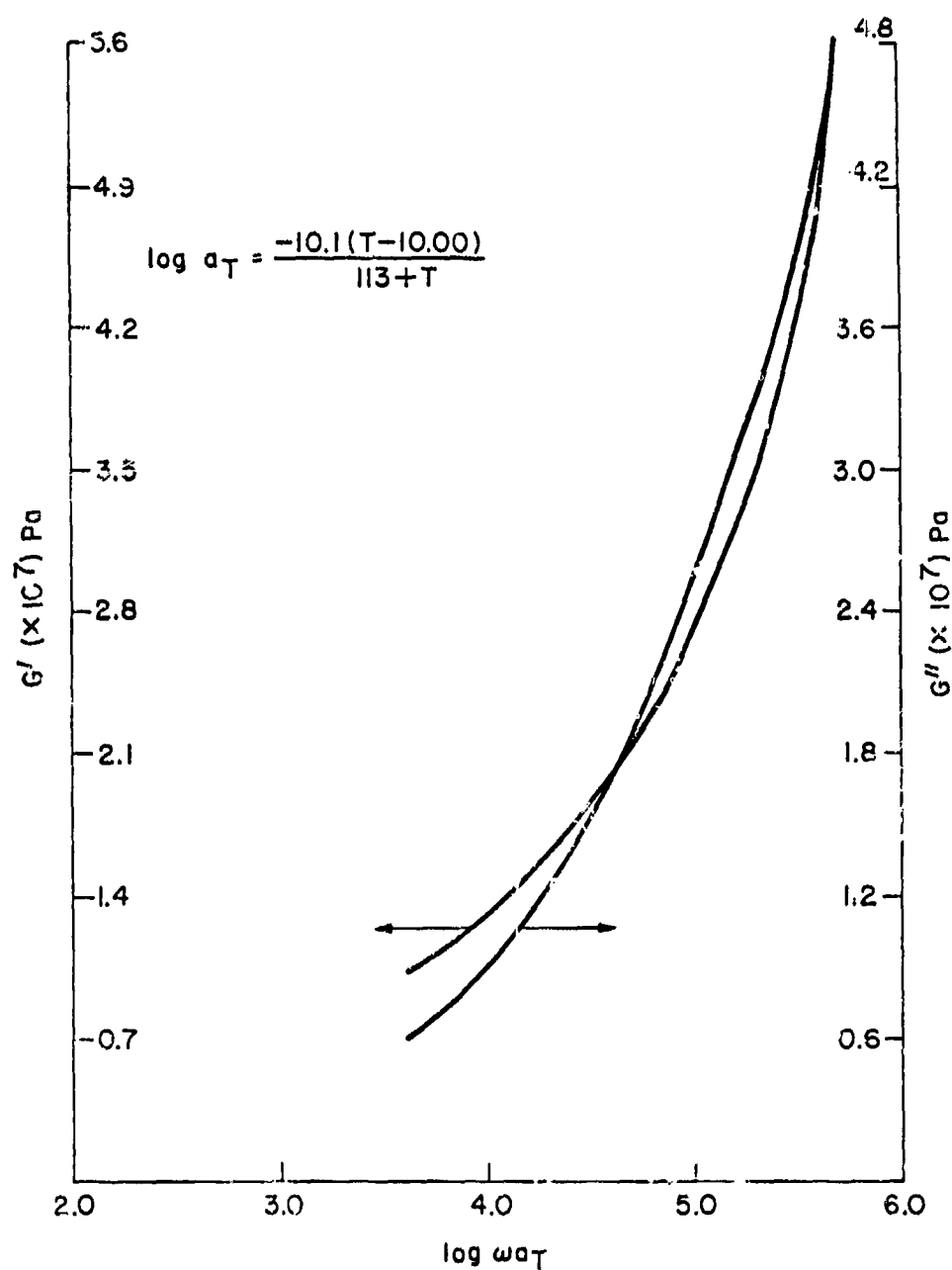
g. *Nitrile Formulations 314-1098 through 314-1101*

(1) Formulation 314-1098 (Ref. 36)

$$\log \ a_T = \frac{-16.41 \ (T-5.00)}{162.3+T}$$
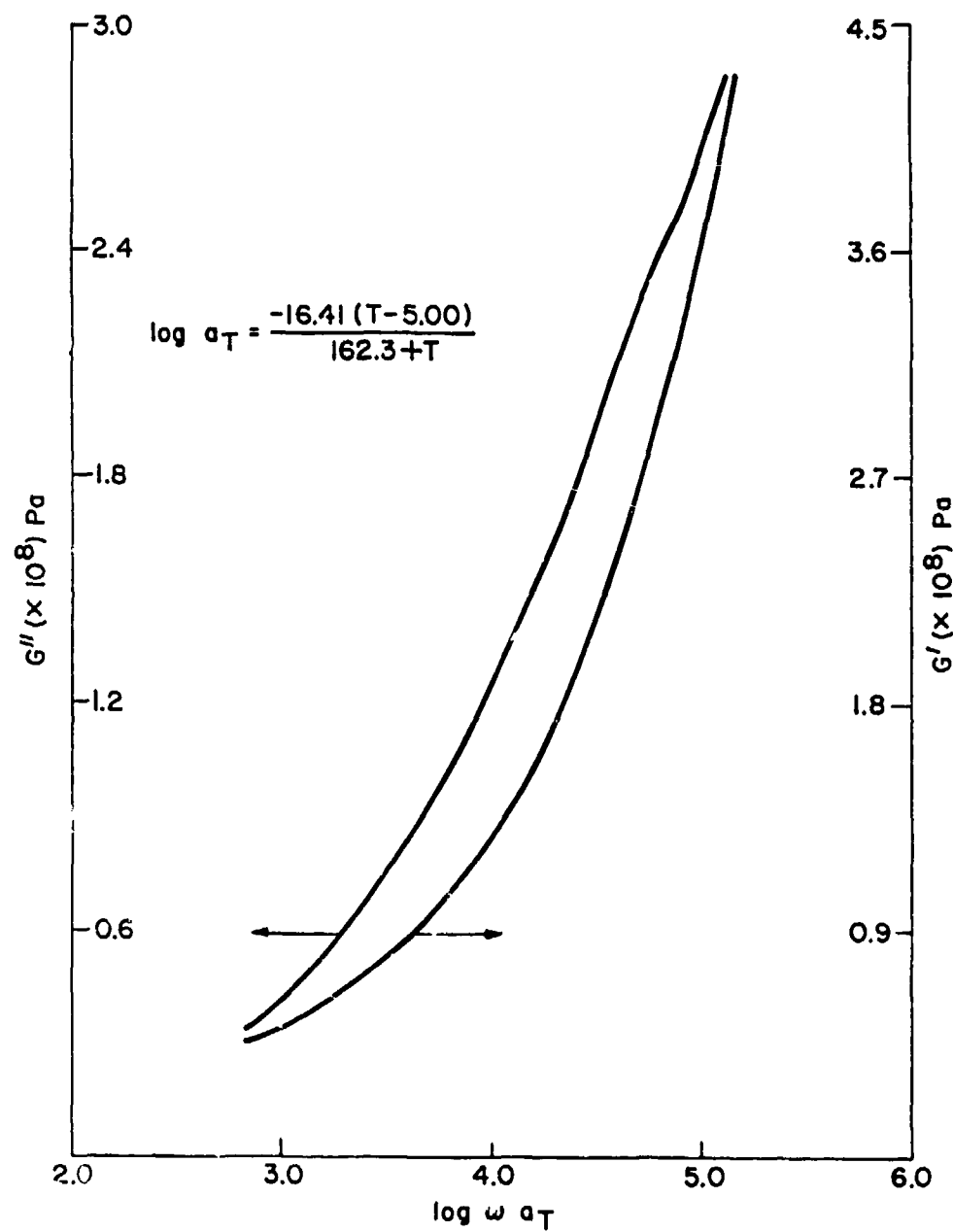
(2) Formulation 314-1099 (Ref. 36)

$$\log a_T = \frac{-3.88\,(T-5.00)}{35.6+T}$$
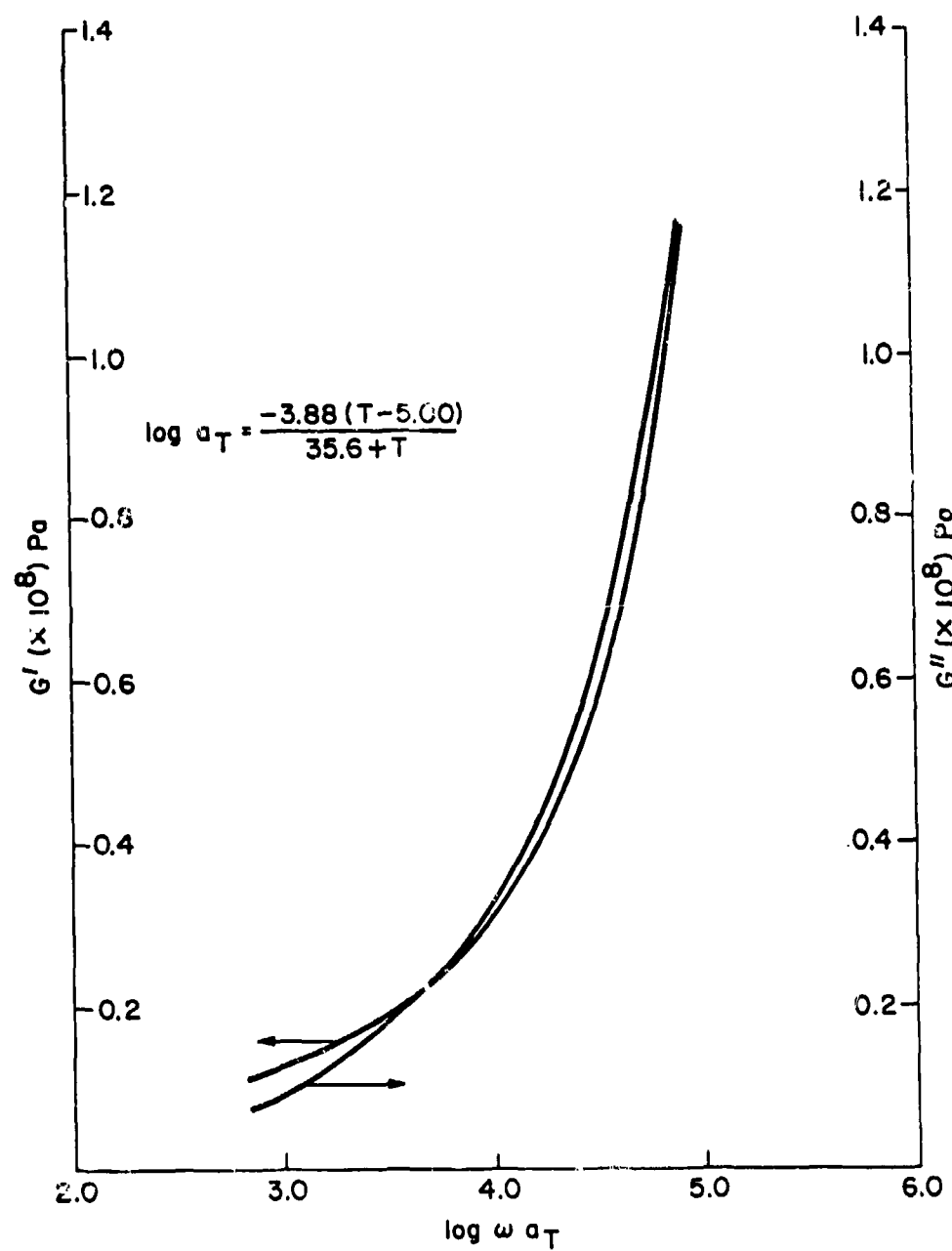
(3)   Formulation 314-1100   (Ref. 36)

$$\log a_T = \frac{-3.96\,(T-5.00)}{30.9+T}$$
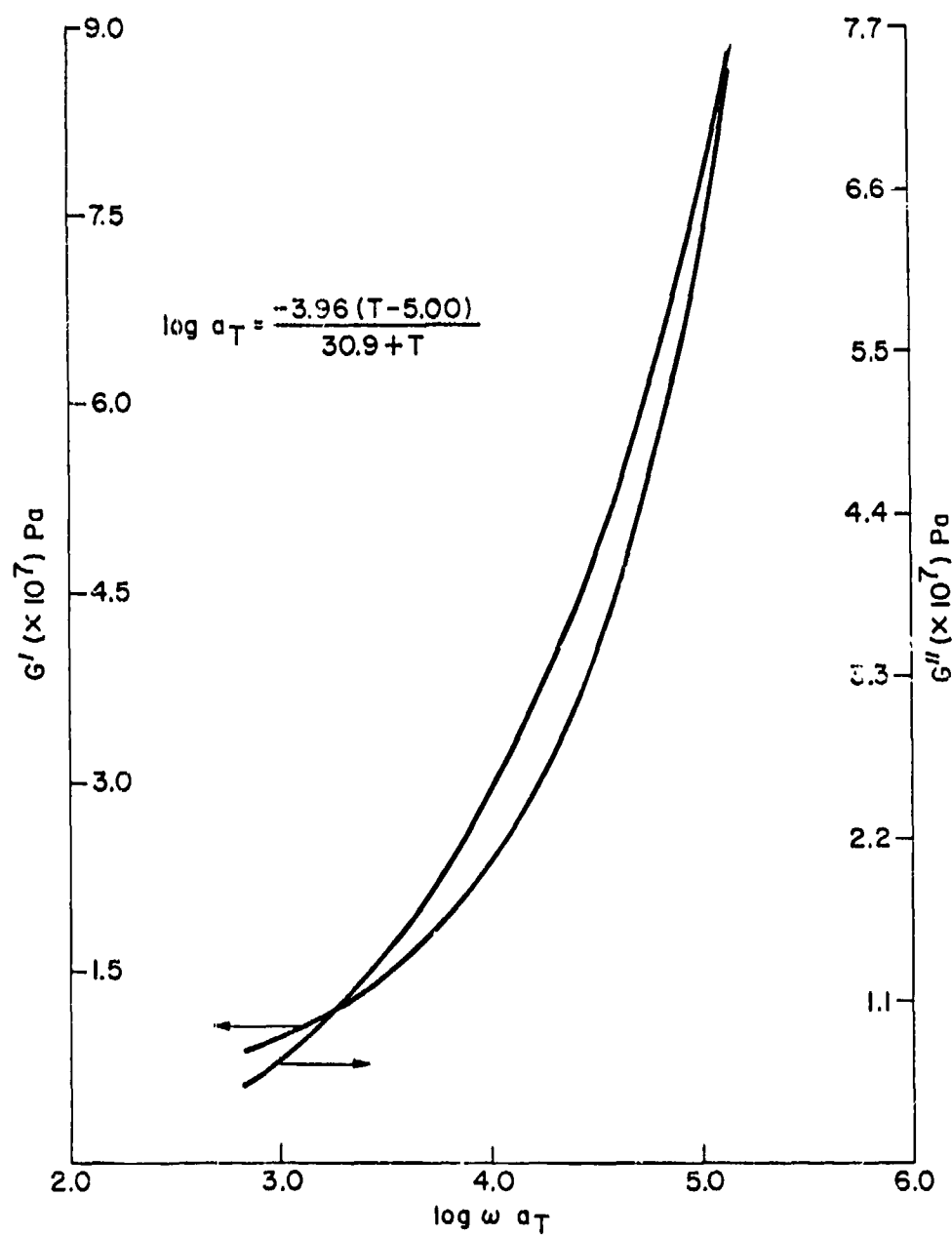
(4) Formulation 314-1101 (Ref. 36)

$$\log a_T = \frac{-4.16 (T - 5.00)}{40.8 + T}$$

128
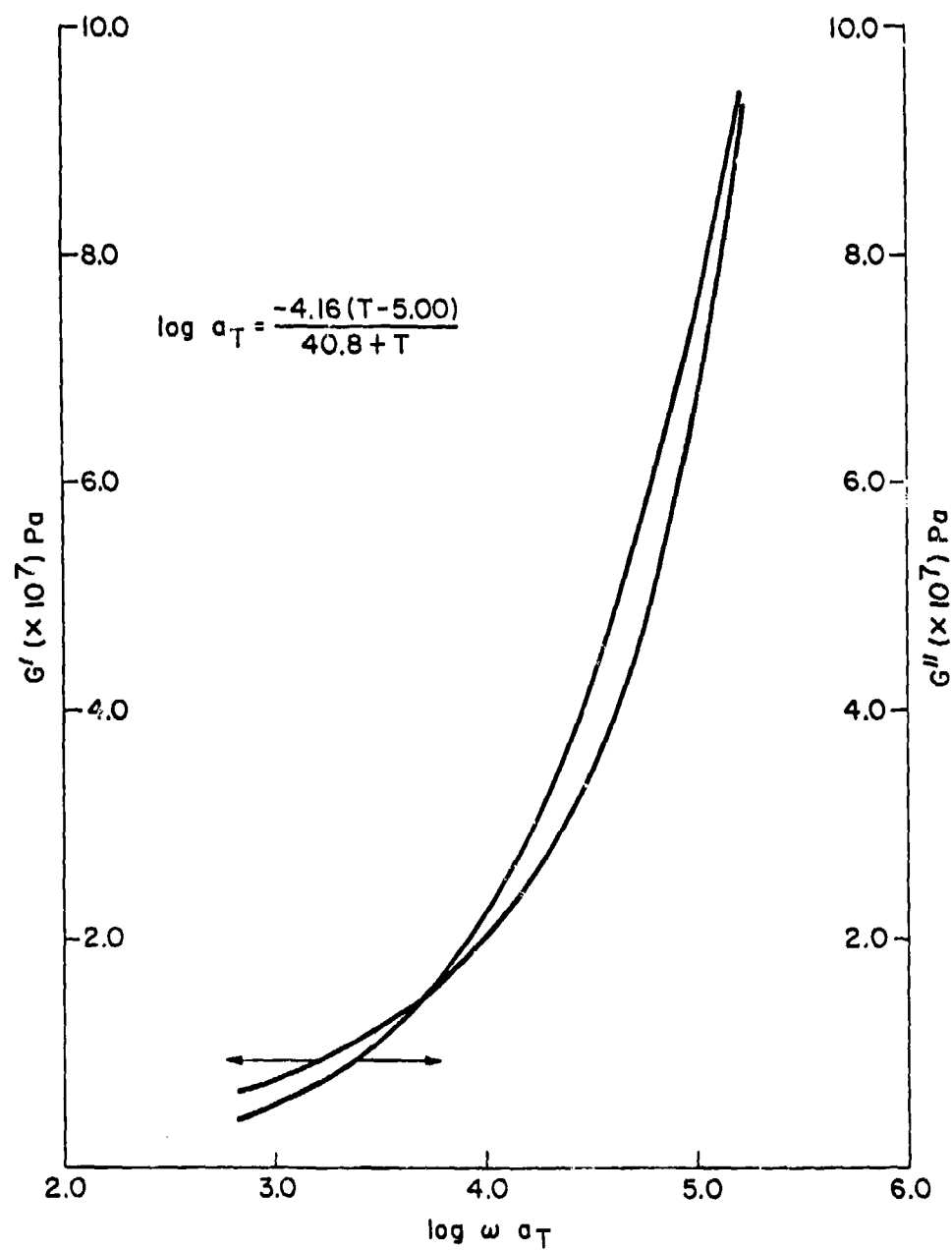
J.   Silicone Rubbers (MQ):   G.E. RTV-31   (Ref. 32)

1.   General Information and Characteristics

General Information:

Silicone rubber is a heat-stable semiorganic rubber. The backbone of the polymer is different from other elastomers in that it contains no carbon. The properties of silicone elastomers are quite different from those of other elastomers. Silicone rubbers have only modest room temperature tensile strength properties, but tend to retain these properties at elevated temperatures. The also have good water resistance and oxidative stability. They are normally crosslinked by peroxides functioning through reaction at an active methyl group or through vinyl substitution. Finely divided silicas or metallic oxides are often used as fillers.

G. E. RTV-31 is a two-package silicone rubber compound. It cures at room temperature after addition of a curing agent, normally dibutyl tin dilaurate.   Normal curing time is twenty-four hours. For faster cures, tin octoate may be used. RTV-31 is a red colored compound which is suitable for sealing, bonding, and encapsulation.

Notable Characteristics:

Retains elastomeric properties at extreme temperatures. Good physical and electrical properties. Good resistance to ozone, weathering, and aging. Low compression set. Excellent live steam resistance. Good resistance to alkalies, oil, and gasoline. High thermal conductivity. Ideal for extension purposes.

Not suited for hydraulic fluid applications. Poor resistance to strong acids, aromatic and chlorinated solvents.

2. Physical Static Properties

Density (g/cm^3) 1.45

Hardness (Shore A) 60

Tensile Strength (MPa) 5.17

Elongation (%) 130

Low Temperature . . . . -59

Stiffness (°C) . . . .

Coefficient of Thermal Expansion
(cm/cm/°C) (-17 to +176°C) . . . . . 2.05×10^{-4}

Dielectric Constant (60 Hz) 4.0

Volume Resistivity (ohm-cm) . . . . . 2.9×10^{15}

Dielectric Strength
(kV/cm, 0.195-cm thick) 187

3. <u>Shear Modulus of GE RTV Silicone</u>   (Ref. 32)
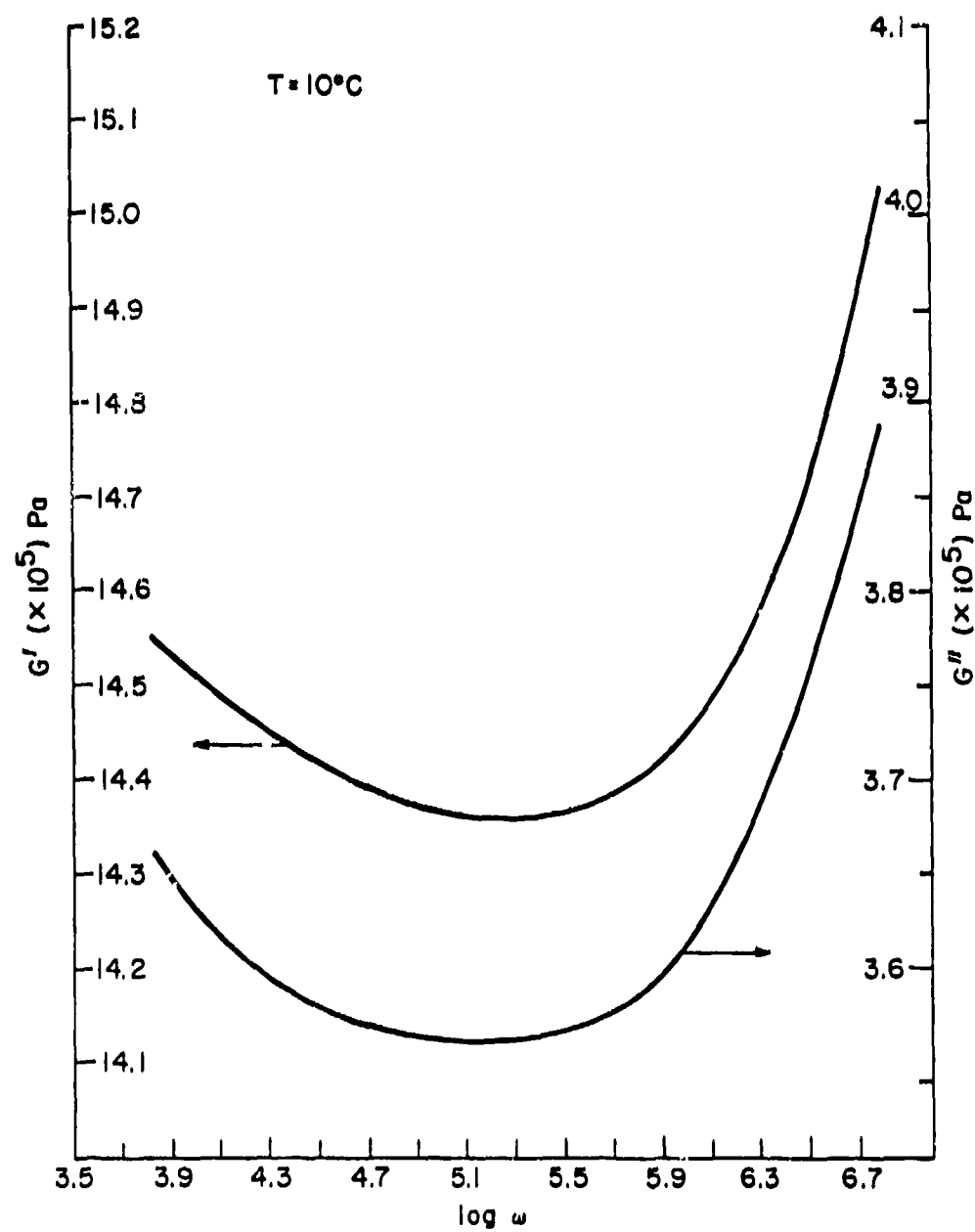
K. Styrene-Butadiene Rubber (SBR)

1. General Information and Characteristics

General Information:

SBR is a general purpose, non-oil resistant rubber manufactured by the copolymerization of butadiene and styrene. Unreinforced SBR has poor tensile properties, therefore carbon black or inorganic fillers, such as silica, calcium silicate, or clay are added to the masterbatch to improve strength. Carbon black filled compounds have lower densities, higher strength, and lower water absorption than mineral filled compounds. Oil extended compounds have strength properties approaching those of the base polymer and exhibit longer dynamic fatigue lives than unextended compounds.

SBR formulations deteriorate quickly in contact with oils and solvents.

Notable Characteristics:

High strength. Excellent abrasion resistance. Low water-absorption.

2. Physical Static Properties

	Carbon Black Reinforced	Carbon Black Reinforced and Oil Extended
Tensile Strength (MPa)	20.0 – 26.2	19.7 – 24.5
Ultimate Elongation (%)	400 – 800	400 – 750
300% Modulus (MPa)	12.2 – 13.8	3.1 – 11.0
Density (g/cm^3)	1.13	1.10
Low-Temperature Stiffness (°C)	–46 to –51°	–57°
Coefficient of Thermal Expansion (cm/cm/°C)	1.71×10^{-3}	1.84×10^{-3}
Volume Resistivity (ohm/cm)	10^{14}	10^{14}
Dielectric Strength (kV/cm)	197	236
Dielectric Constant	4	3 – 7
Hardness (Shore A)	60	70
Water Absorption (mg/cm^2) 7 days	3.1	--

3. Compounding Recipes

Compounding recipes and cure times were not available (References 38 and 39).

4. <u>Bulk Modulus for Styrene-Butadiene Rubber (SBR)</u>

(Ref. 38)

$$T_R = 10°C$$

$$\log a_T = \frac{-8.86(T-20)}{81.6+T}$$
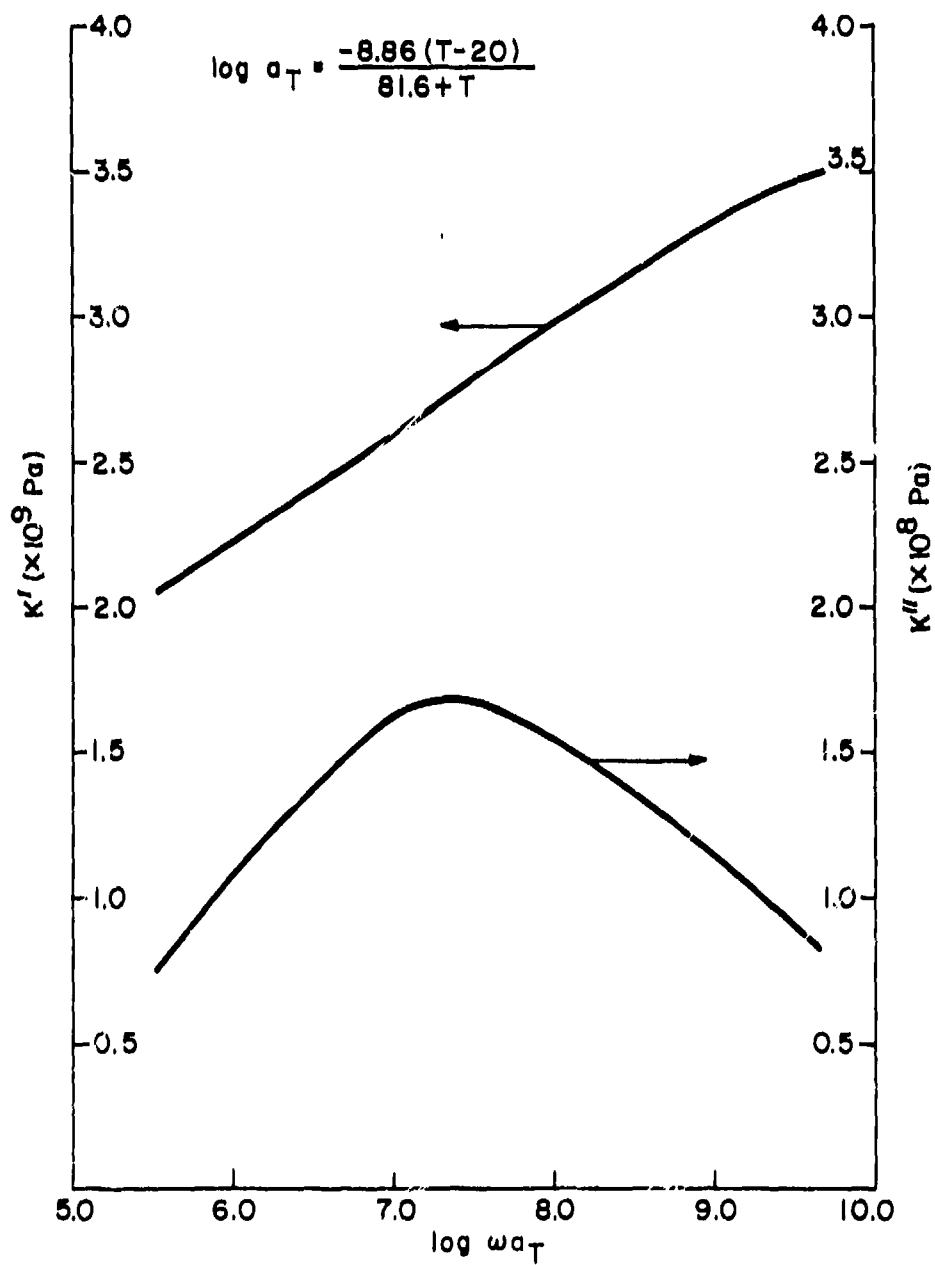
5. <u>Shear Modulus of Styrene-Butadiene Rubber (SBR)</u>

<div align="right">(Ref. 39)</div>

$$T_R = 10°C$$

$$\log a_T = \frac{-8.86 (T - 20)}{81.6 + T}$$
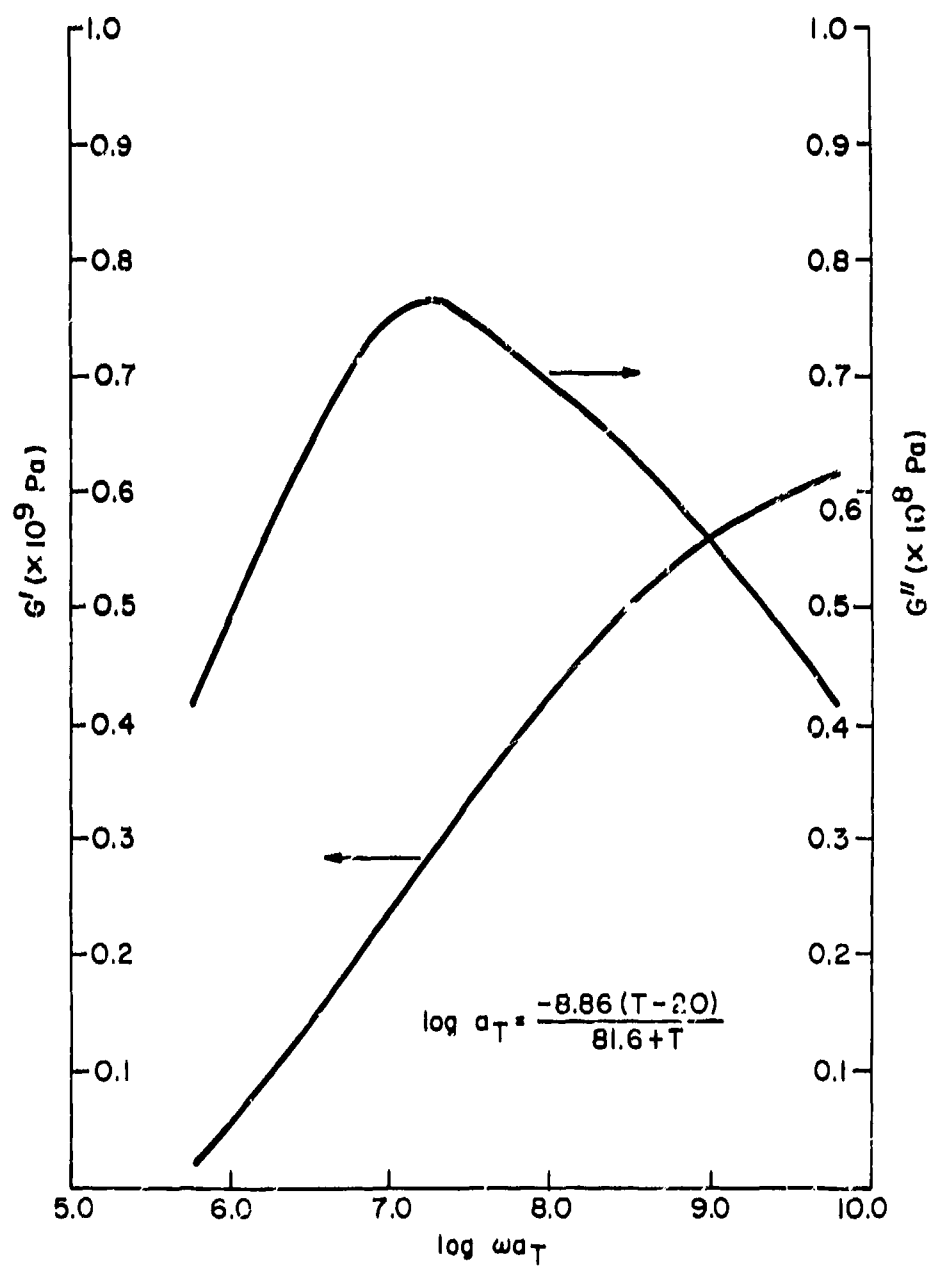
L. Urethane Rubber (U)

1. General Information and Characteristics

General Information: The urethane elastomers constitute a family of
                        materials derived from the reaction of isocyanates
                        with polyesters or polyethers. Most types are
                        cured without sulfur. Polyurethanes may be
                        subdivided into liquid casting systems or millable
                        urethane elastomers. The liquid casting systems
                        are further divided into polyether and polyester
                        systems, while the millable elastomers are
                        divided into cross-linkable rubbers, and thermo-
                        plastic polymers. For further specifics,
                        the reader should consult reference 5.

                        Information contained here is for a series of
                        liquid polyurethane casting systems manufactured
                        by Products Research and Chemicals and Conap, Inc..
                        These are all two-component systems. Some are
                        MOCA-cured and some are not. For specific
                        applications and handling procedures, the manufac-
                        turer's literature should be consulted.

Notable Characteristics: Very good electrical properties, especially
                        dielectric strength in thin films, and high
                        volume sensitivity. High strength and shear
                        resistance. Good abrasion resistance. High
                        damping characteristics, poor heat buildup
                        characteristics, excellent resistance to alcohols,
                        aliphatic solvents, ether, and most petroleum
                        based fuels up to 120°C, edible fats and oils, and
                        mixtures containing less than 80% aromatics, ozone,
                        and oxygen.

                        Unsuitable for contact with esters, ketones,
                        synthetic hydraulic oils, concentrated acids and
                        bases, hot water and steam.

2. Polyurethane PR-1524 Potting Compound

PR-1524 is especially formulated for use as a molding compound for electrical cables or a potting compound for electrical connectors where low Shore A hardness, resistance to cold flow, extra flexibility, and exposure from -62 to +135°C for prolonged periods are required. PR-1524 is MOCA-cured.

a. *Physical Properties of PR-1524* (cured 7 days at 24°C or 16 hours at 82°

Tensile Strength (MPa)	6.90
Ultimate Elongation (%)	400
Hardness (Shore A)	50
Fungus Resistance	Non-nutrient
Volume Shrinkage (%)	4
Useful Temperature Range	-62 to +135°C
Volume Resistivity (ohm-cm).	1×10^{12}@ 24°C & 2×10^{5} @ 82°C
Density (g/cm³)	1.05

Dielectric Strength
(kV/cm re 0.318-cm thickness) . . . 130

Dielectric Constant at 24°C:

at 1 kHz	7.8
at 10 kHz . . .	7.2
at 1 MHz	4.8

Tear Strength (Die C) (lbs./in.) . . 100

Compression Set (%)
(ASTM D395, Method B) 27

Adhesion*, peel, lbs./in. of width:

Aluminum Alloy	40
Cadmium Plate	40
Neoprene	30
Polyvinyl Chloride	20

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*Metals were primed with PR-420; neoprene was buffed but no primer was used; polyvinyl chloride was tackified with methyl ethyl ketone and primed with PR-1543.

b. *Relative transmission loss as a function of incident angle and frequency* [Ref. 40].
Sample Size: 30.48 × 30.48 × 2.11 cm [see Ref. 41 for measurement technique].
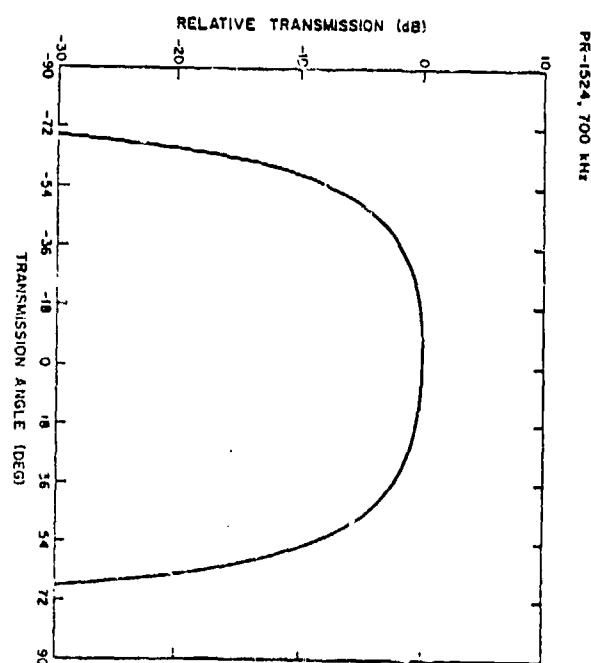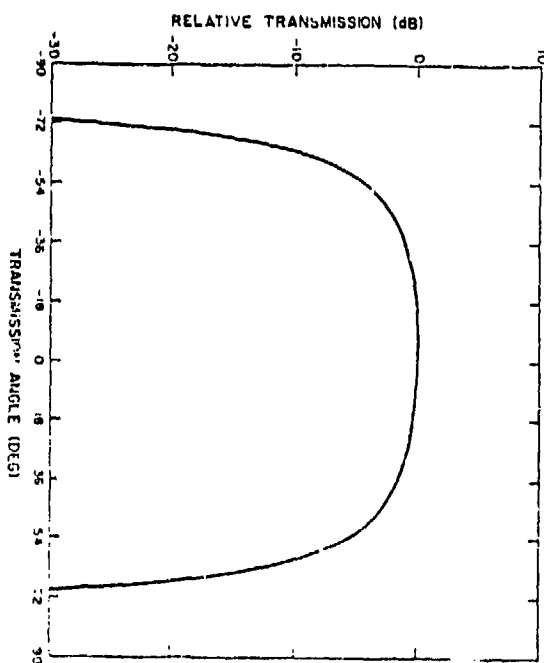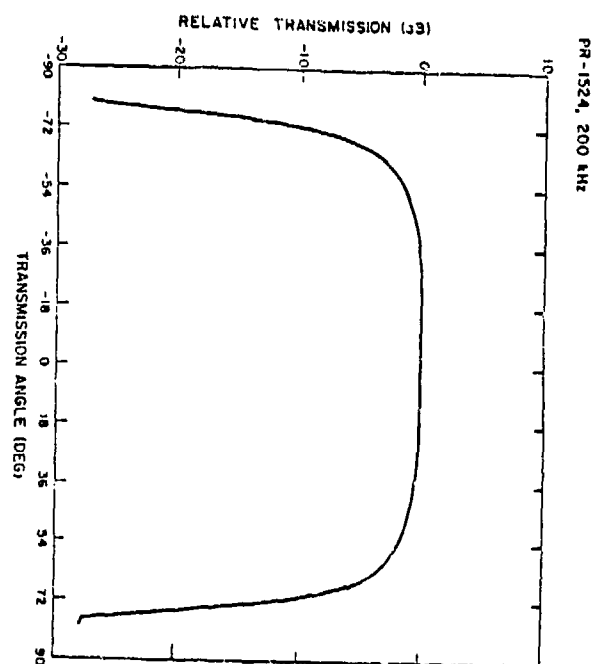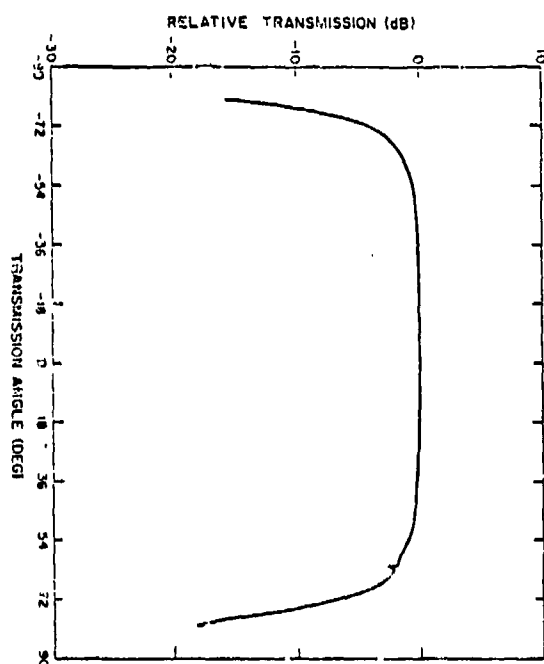
3. Polyurethane PR-1527 Potting Compound

a. *General Information*

PR-1527 is especially formulated for use as a molding compound for electrical cables or potting compound for electrical connectors where resistance to cold flow, high tensile strength, and exposure to extreme temperatures for prolonged periods are required. PR-1527 is MOCA cured.

b. *Physical Properties* (cured 16 hours at 82°C)

Tensile Strength (MPa) 17.2

Ultimate Elongation (%) 550

Hardness (Shore A) 80

Fungus Resistance . . . . Non-nutrient

Volume Shrinkage (%) 4

Useful Temperature Range . . . . . . -62 to +149°C

Volume Resistivity (ohm-cm) . . . . . 1.0×10^{12} @ 24°C and 1.3×10^{9} @ 149°C

Density (g/cm^3) 1.06

Dielectric Strength (kV/cm
re 0.318-cm thickness) 122

Dielectric Constant at 24°C:

At 1 kHz 8.3
At 1 Mhz 6.2

Tear Strength (Die C) (lbs./in.) . . 225

Compression Set (ASTM D395,
Method B) 24%

Adhesion*, peel, lbs./in. of width:

Aluminum Alloy 50
Cadmium Plate 50
Neoprene 25
Polyvinyl Chloride 30

---

*Metals were primed with PR-420; neoprene was buffed but no primer was used; polyvinyl chloride was tackified with methyl ethyl ketone and primed with PR-1543.

c. *Relative transmission loss as a function of incident angle and frequency* [Ref. 40]

Sample Size: 30.48 × 30.48 × 1.01 cm; T = 23.8°C [See Ref. 41 for measurement technique].
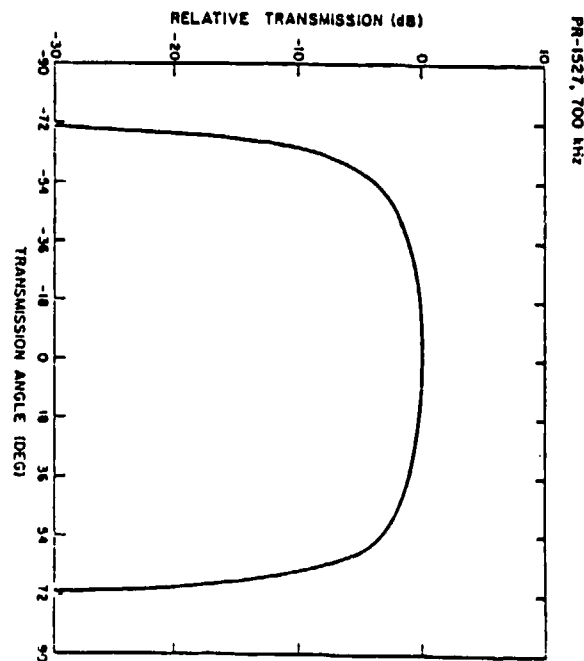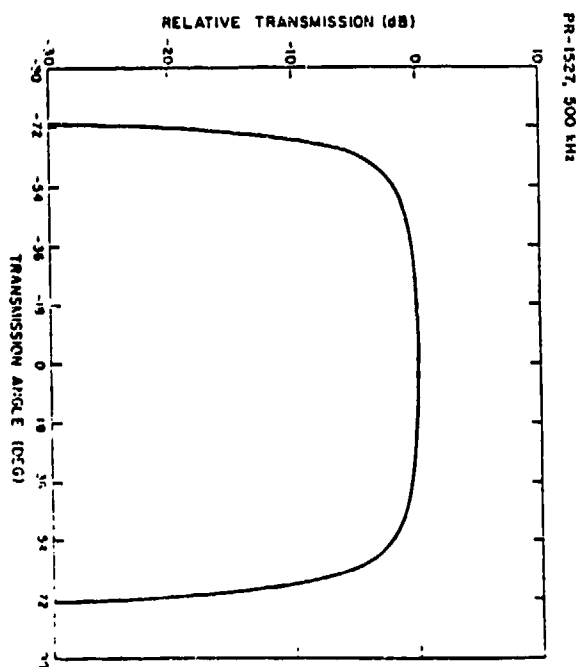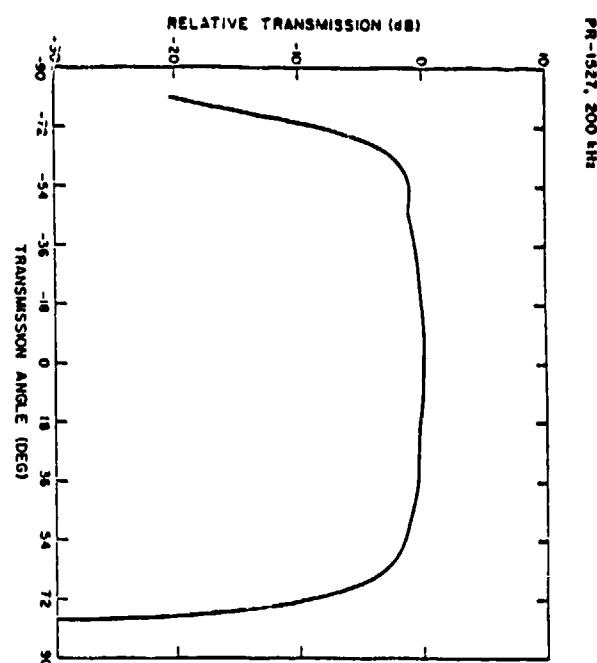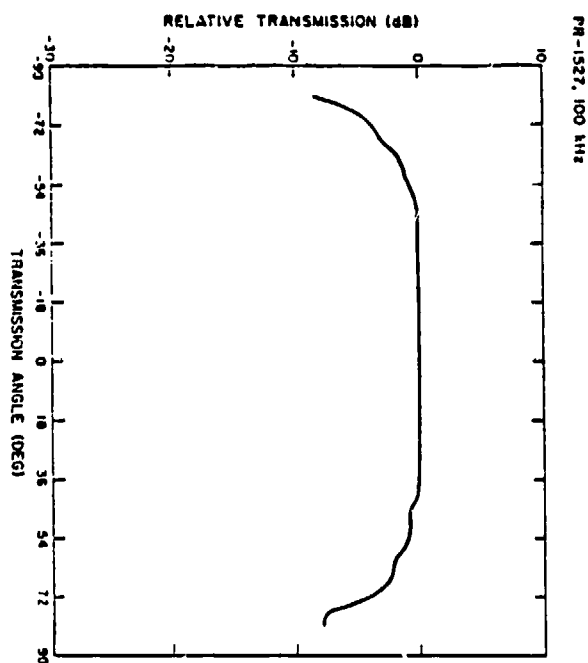
d. *Shear Modulus of PR-1527* (Ref. 32)
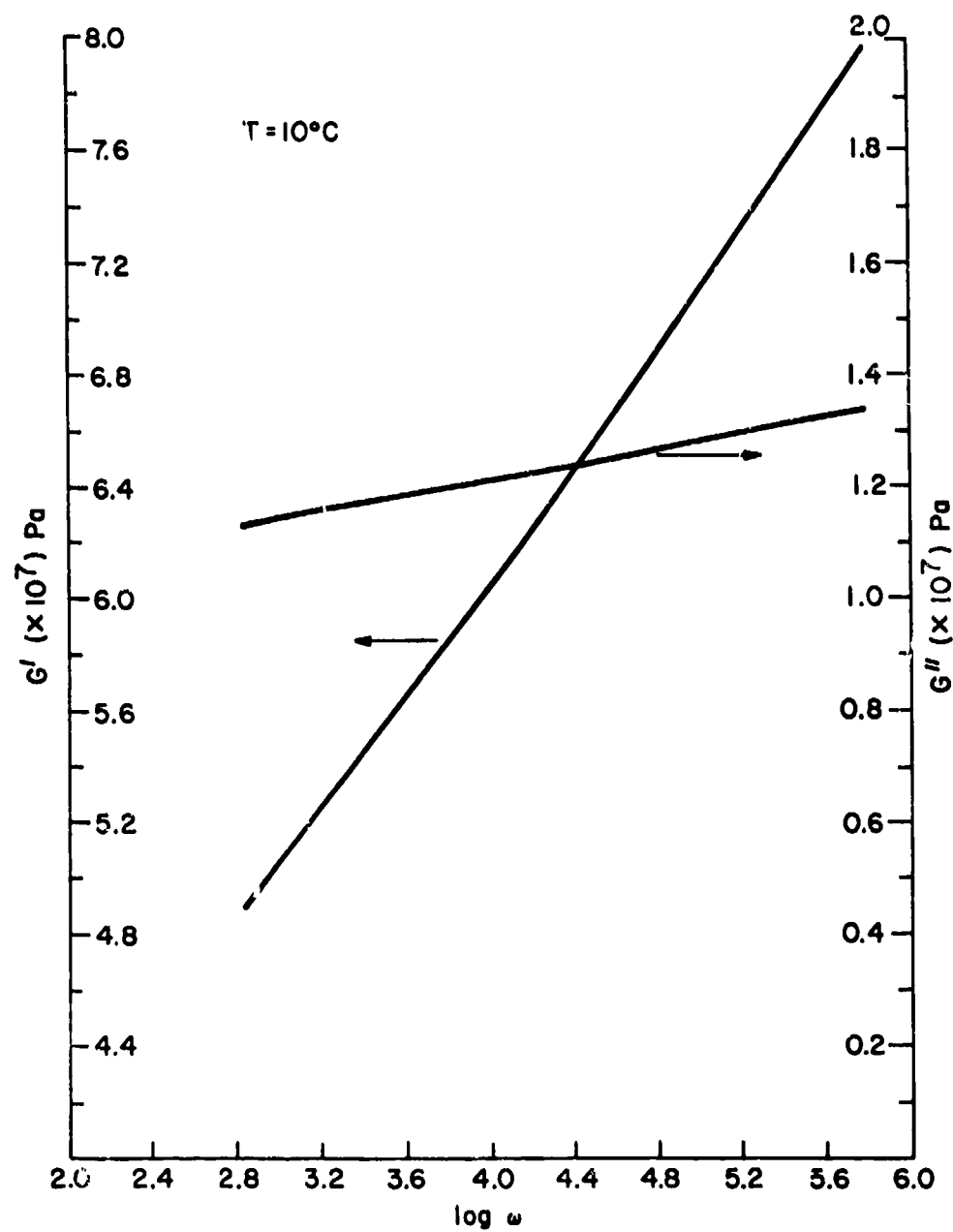
4. Polyurethane PR-1538 Potting Compound

a. *General Information*

PR-1538 is formulated for use as a low-viscosity potting compound for electrical connectors, a molding compound for electrical cables and mechanical parts, a circuit-board coating, and an electrical imbedding compound. It is a MOCA-cured system.

b. *Physical Properties* (cured 16 hours at 82°C)

Tensile Strength (MPa) 20.9

Ultimate Elongation (%) 600

Hardness (Shore A) 80

Fungus Resistance . . . . Non-nutrient

Volume Shrinkage (%) 1.4

Useful Temperature Range . . . . . . -57 to +149°C

Volume Resistivity (ohm-cm) . . . .

Density (g/cm^3) 1.05

Dielectric Strength
(kV/cm re 0.318-cm thickness) . . . 108

Water Permeability
(10^{-10}gH_2O-cm/cm^2/hr./torr) 4220

Dielectric Constant at 24°C:

  At 1 kHz 6.8
  At 10 kHz 6.2
  At 1 MHz 4.4

Tear Strength (Die C) (lbs./in.) . . 200

Compression Set (%)
(ASTM D395, Method B) . . . . 10 at 24°C

Coefficient of Thermal
Expansion (cm/cm/°C) . . . . 4.50×10^{-4}

Adhesion*, peel, lbs./in. of width:

  Aluminum Alloy 30
  Cadmium Plate 40
  Neoprene 25
  Polyvinyl Chloride 25

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*Metals were primed with PR-420; neoprene was buffed but no primer was used; polyvinyl chloride was tackified with methyl ethyl ketone and primed with PR-1543.

c. *Relative transmission loss as a function of incident angle and frequency* (Ref. 40)

Sample Size: 30.48 × 30.48 × 2.02 cm;   T = 21.8°C   [see Ref. 41 for measurement technique].
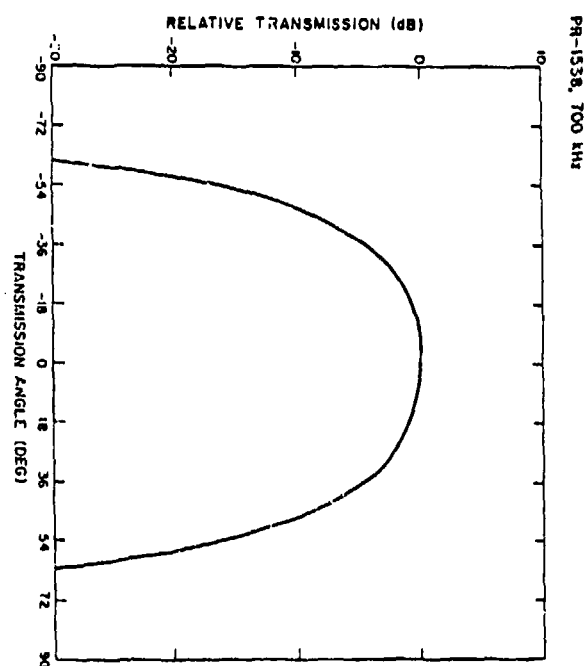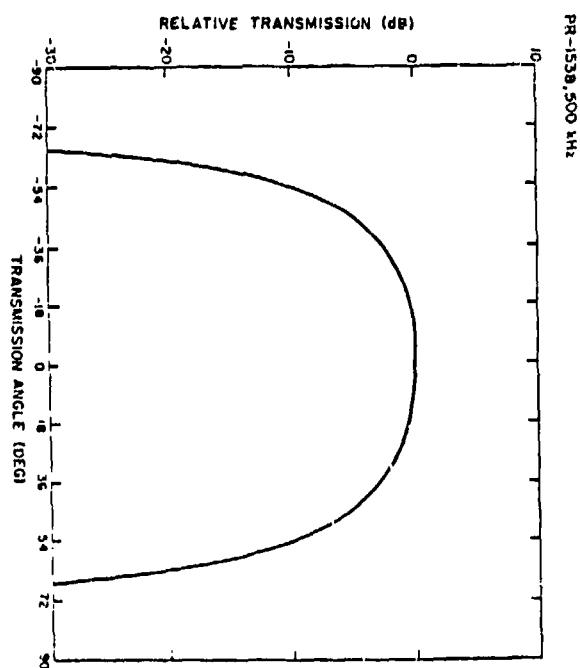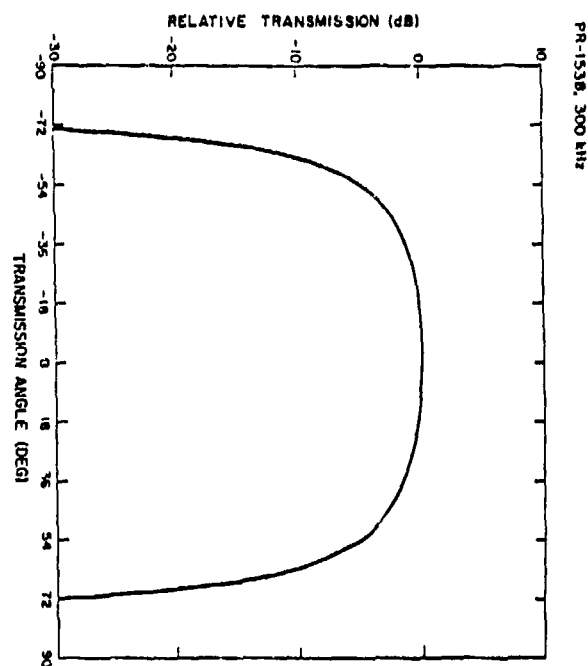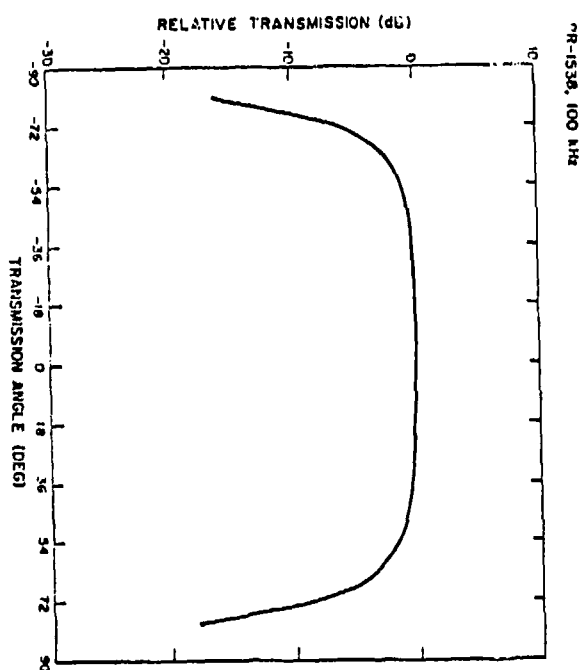
5. Polyurethane PR-1564 Potting Compound

a. *General Information*

PR-1564 is formulated for use as a low viscosity molding compound for electrical cables or a potting compound for electrical connectors in cases where moderate Shore A hardness, resistance to cold flow, extra flexibility and exposure from -62 to +135°C are required. PR-1564 contains no MOCA.

b. *Physical Properties* (cured for 16 hrs. at 82°C)

Tensile Strength (MPa) 6.9

Ultimate Elongation (%) 300

Hardness (Shore A) 60

Fungus Resistance . . . . Non-nutrient

Volume Shrinkage 4

Useful Temperature Range . . . . -62 to +135°C

Volume Resistivity (ohm-cm) . . . . 1×10^{12} @ 24°C and 4×10^{8} @ 135°C

Density (g/cm^3) 1.06

Dielectric Strength
(kV/cm re 0.318-cm thickness) . . . 132

Dielectric Constant at 24°C:

  At 1 kHz 7.0
  At 1 MHz 4.3

Tear Strength (Die C) (lbs./in.) . . 80

Adhesion*, peel, lbs./in. of width:

  Aluminum Alloy 25
  Cold Rolled Steel 25
  Neoprene 25
  Polyvinyl Chloride 25

- - - - -

*Metals were primed with PR-420; neoprene was buffed but no primer was used; polyvinyl chloride was tackified with methyl ethyl ketone and primed with PR-1543.

c. *Relative transmission loss as a function of incident angle and frequency* (Ref. 40).

Sample Size: 30.48 × 30.48 × 1.79 cm; T = 20.5°C [see Ref. 41 for measurement technique].

145
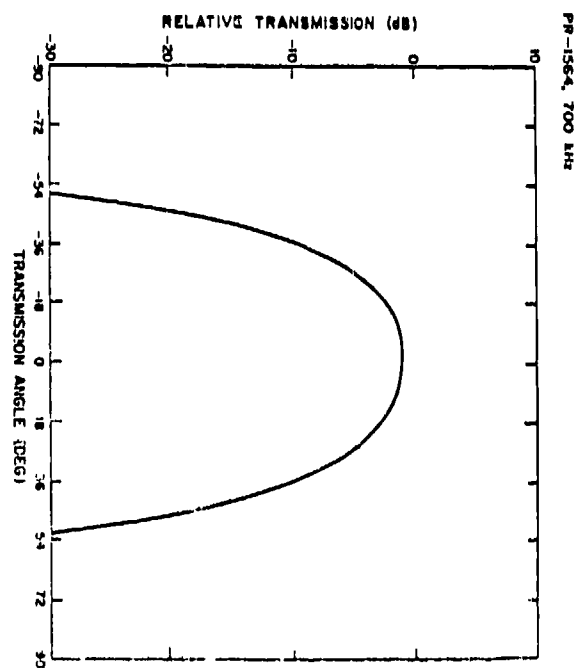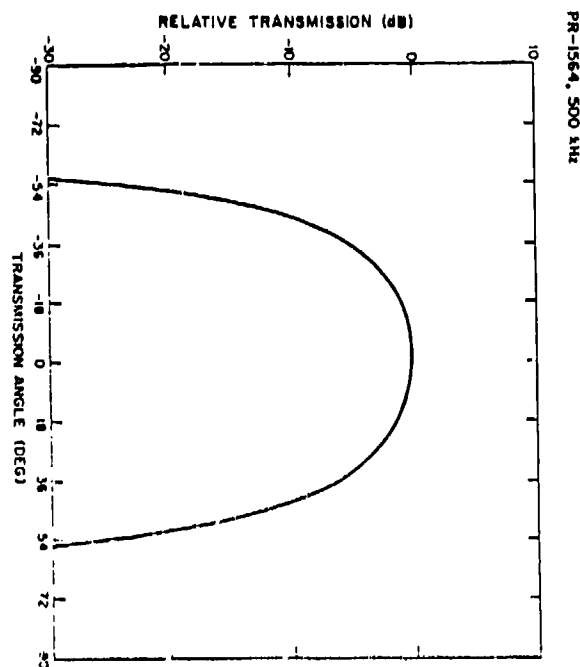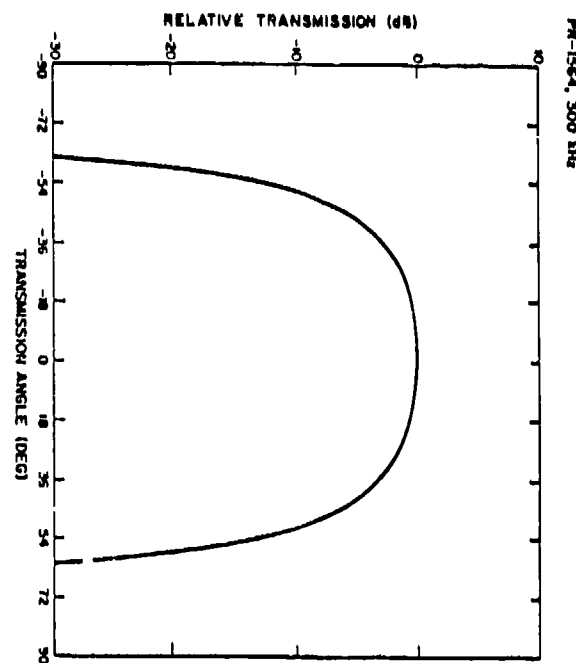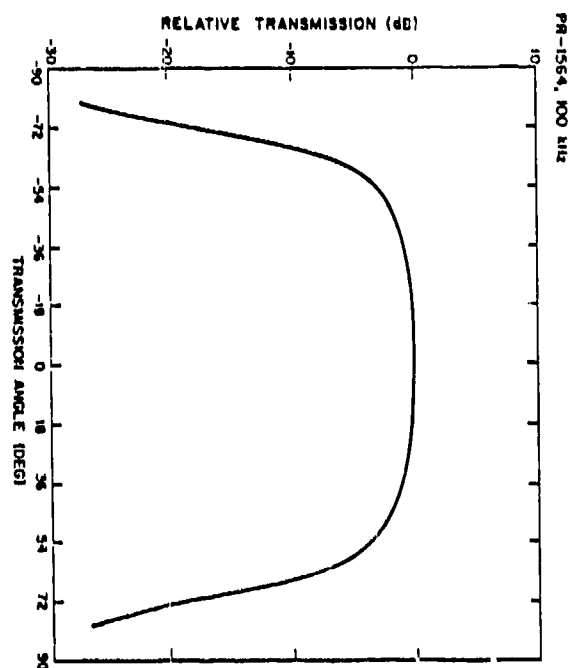
d. *Young's Modulus for PR-1564* (Ref. 42)
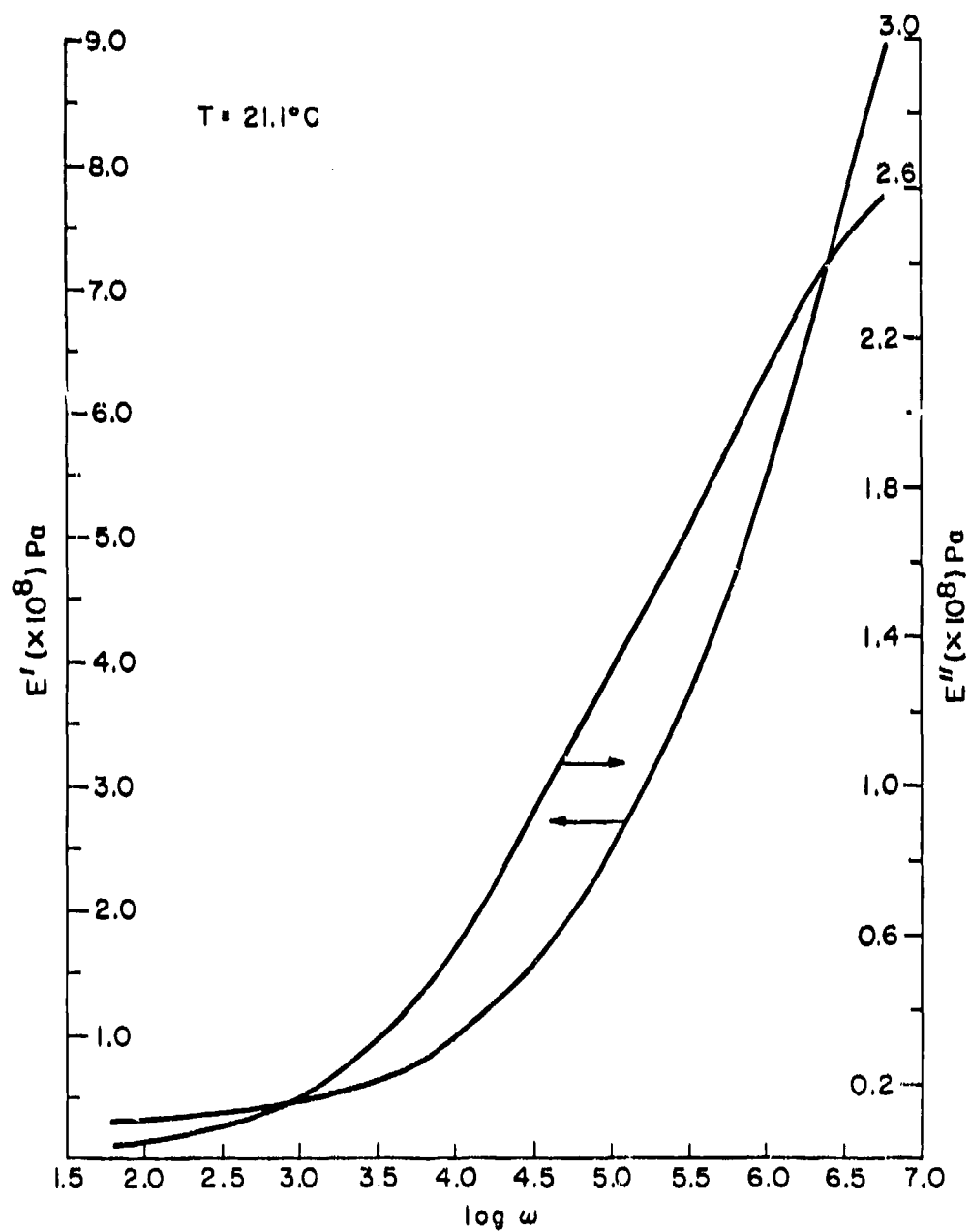
6. Polyurethane PR-1570 Potting Compound

a. *General Information*

PR-1570 is formulated for use as a medium hardness potting and molding compound for use in cases where outstanding retention of electrical properties under conditions of high humidity and temperature is desired. It i· a non-MOCA cured system.

b. *Physical Properties* (cured 16 hours at 82°C)

Tensile Strength 6.90

Ultimate Elongation (%) . . . 350

Hardness (Shore A) 75

Fungus Resistance . . . . . . Non-nutrient

Volume Shrinkage (%) 4

Useful Temperature Range . . . -57 to +121°C

Volume Resistivity (ohm-cm) . 1×10^{15} @ 24°C and 1×10^{12} @ 121°C

Density (g/cm³) 0.98

Dielectric Strength
(kV/cm re 0.318-cm thickness) 132

Water Permeability at 24°C
(10^{-10} g H_2O-cm/cm²/hr./torr) , 900

Sound Velocity in Seawater
(200 kHz, 19.4°C) . . . . . . 1581 m/s

Dielectric Constant at 24°C:
  at 1 kHz 3.2
  at 1 MHz 2.7

Tear Strength (Die C) (lb./in.) 100

Compression Set (%)
(ASTM D395, Method B) 28

Adhesion*, peel, lbs./in. of
width:

  Aluminum Alloy 50
  Stainless Steel 50
  Neoprene 20
  Polyvinyl Chloride 20

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*Metals were primed with PR-420; neoprene was buffed but no primer was used; polyvinyl chloride was tackified with methyl ethyl ketone and primed with PR-1543. Stainless Steel was also primed with PR-420; neoprene was wiped with methyl ethyl ketone.

c. *Relative transmission loss as a function of incident angle and frequency* (Ref. 40)

Sample Size: 30.48 × 30.48 × 1.61 cm; T = 20.5°C [see Ref. 41 for measurement techniques].
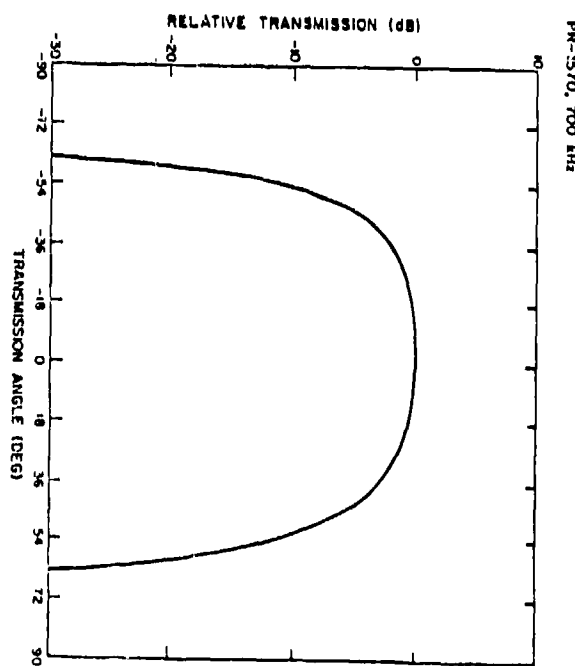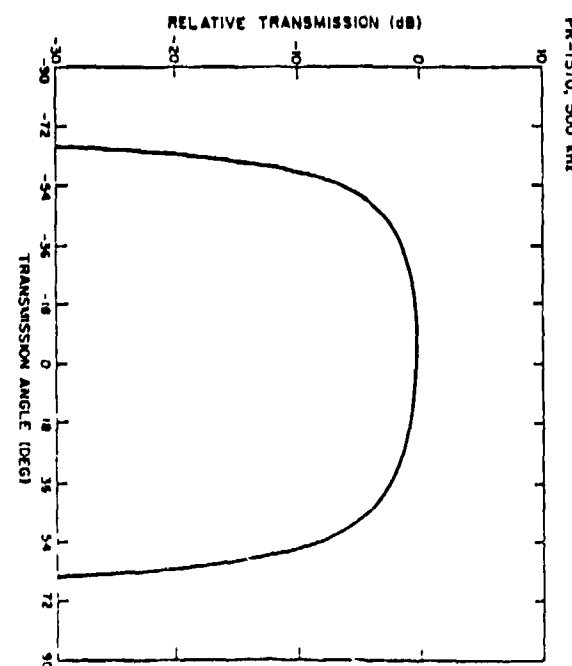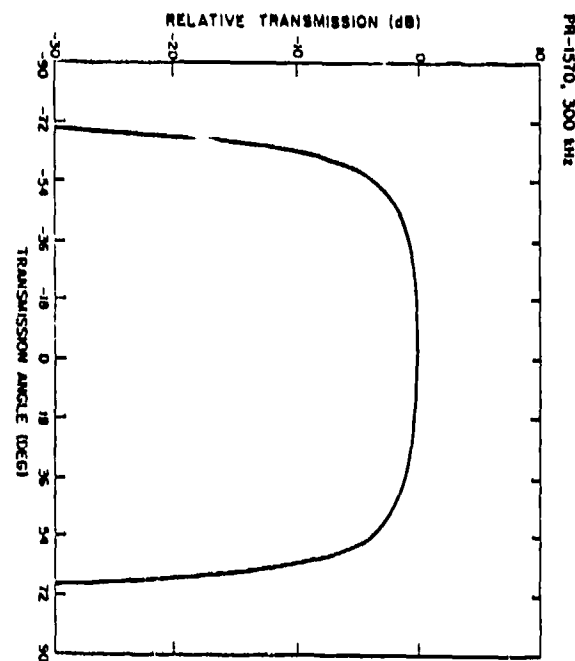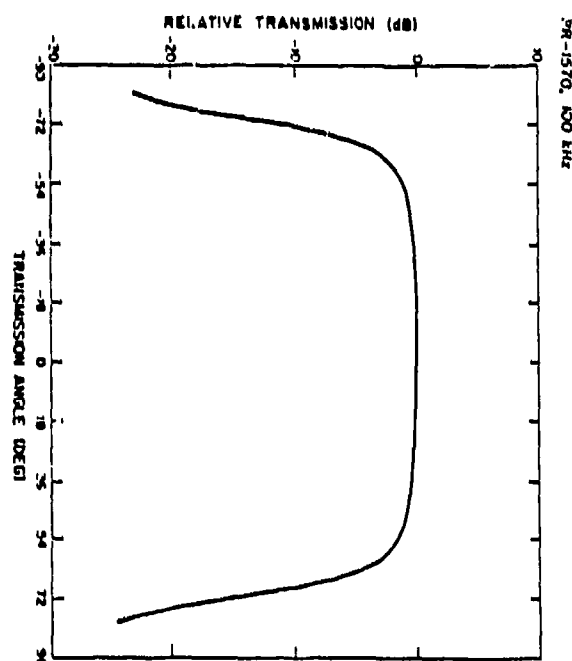
7. Polyurethane PR-1574 Potting Compound

a. *General Information*

PR-1574 is formulated for use as a low-viscosity, high-hardness potting or molding component for use in cases where outstanding retention of electrical properties under conditions of high humidity and temperature is desired. It does not contain MOCA.

b. *Physical Properties* (cured 16 hrs. at 82°C)

Tensile Strength (MPa) 17.2

Ultimate Elongation (%) 425

Hardness (Shore A) 90

Volume Shrinkage (%) 3.5

Useful Temperature Range . . . . -57 to +121°C

Volume Resistivity (ohm-cm) . . . . . 1×10^{15} @ 24°C and 1×10^{12} @ 121°C

Density (g/cm^3) 0.98

Dielectric Strength
(kV/cm re 0.318-cm thickness) 130

Water Permeability
(10^{-10}g H_2O-cm/cm^2/hr./torr). 900

Dielectric Constant at 24°C:

    at 1 kHz 2.8
    at 1 MHz 2.6

Tear Strength (Die C) (lbs./in.) . . . 300

Adhesion*, peel, lbs./in. of width:

    Aluminum Alloy 50
    Stainless Steel 50
    Neoprene 20
   Polyvinyl Chloride 20

- - - - - - - - - -

*Metals were primed with PR-420; neoprene was buffed but no primer was used; polyvinyl chloride was tackified with methyl ethyl ketone and primed with PR-1543. Stainless Steel was also primed with PR-420; neoprene was wiped with methyl ethyl ketone.

c. *Shear Modulus of PR-1574* (Ref. 32)

150
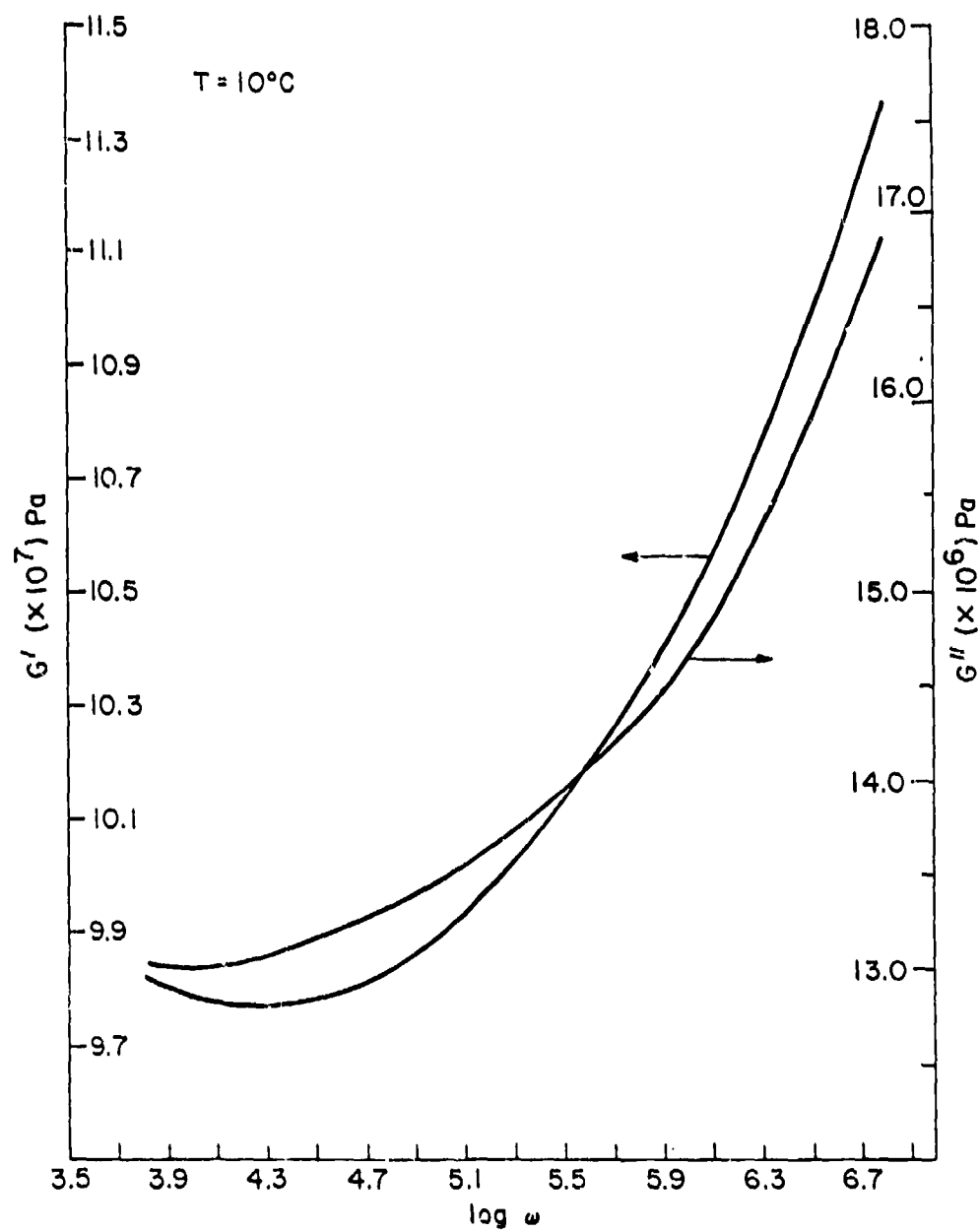
8. Polyurethane PR-1590 Potting Compound

    a. *General Information*

        PR-1590 is formulated for use as a low-viscosity mold-ing compound for electrical cables and a potting compound for electrical connectors where a medium hardness, resistance to cold flow, and exposure to extreme temperatures for prolonged periods are required. PR-1590 is a MOCA-free compound.

    b. *Physical Properties* (cured 16 hrs. at 82°C)

Tensile Strength (MPa) 15.2

Ultimate Elongation (%) 500

Hardness (Shore A) 75

Fungus Resistance . . . . Non-nutrient

Volume Shrinkage (%) 4

Useful Temperature Range . . . . -57 to +121°C

Volume Resistivity (ohm-cm) . . . . . 1×10^{12} @ 24°C and 1×10^9 @ 121°C

Density (g/cm^3) 1.08

Dielectric Strength (kV/cm) 118

Dielectric Constant at 24°C:

  at 1 kHz 7.4
  at 1 MHz 4.8

Tear Strength (Die C) (1bs./in.) . . . 175

Compression Set (%)
(ASTM D395, Method B) 34

Adhesion*, peel, 1bs./in. of width:

  Aluminum Alloy 40
  Neoprene 25
Polyvinyl Chloride 28

- - - - - - - - - -

*Metals were primed with PR-420; neoprene was primed with PR-1543-M and buffed; polyvinyl chloride was tackified with methyl ethyl ketone but no primer was used.

c. *Relative transmission loss as a function of incident angle and frequency* (Ref. 40)

Sample Size: 30.48 × 30.48 × 1.95 c.n; T = 17.2°C [see Ref. 41 for measurement technique].
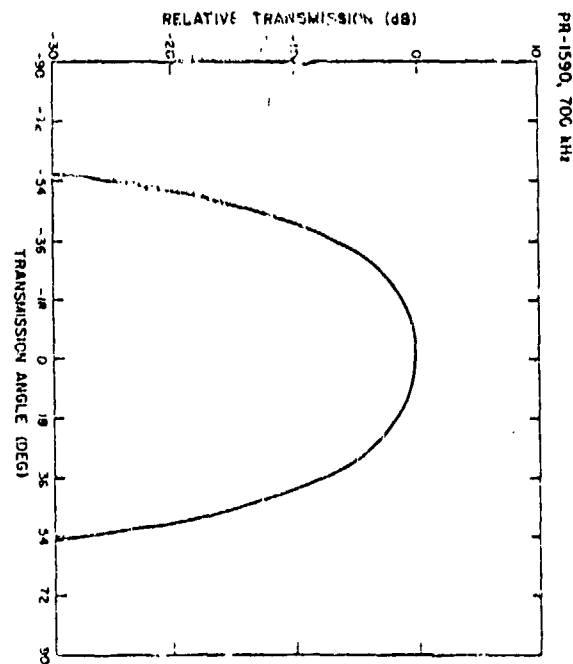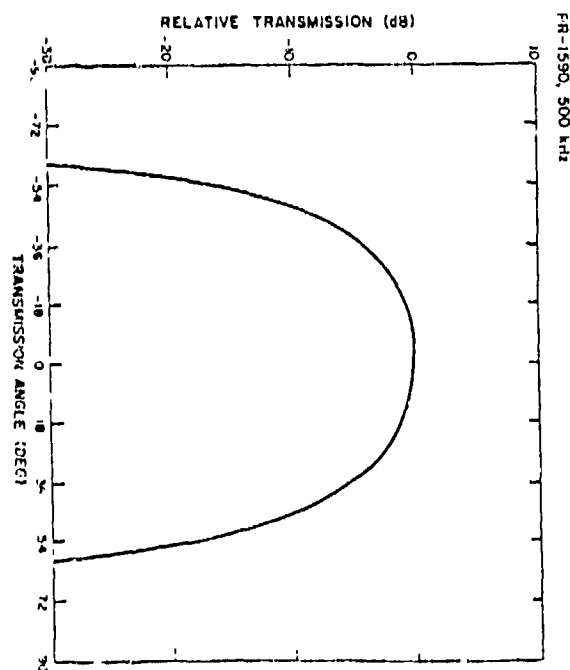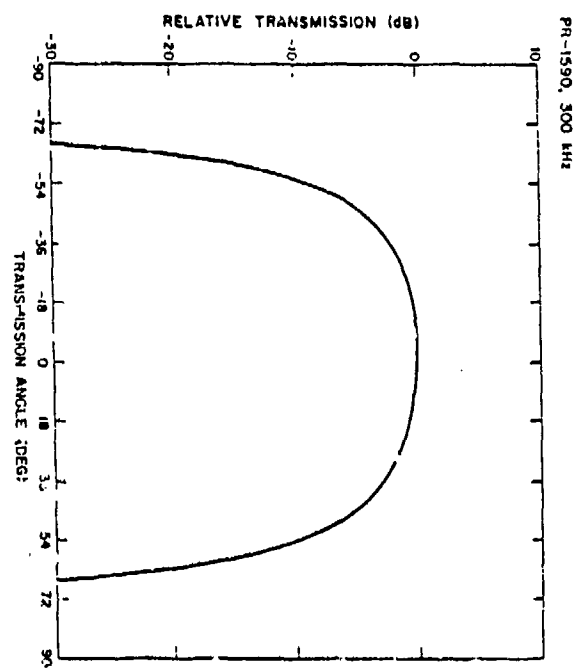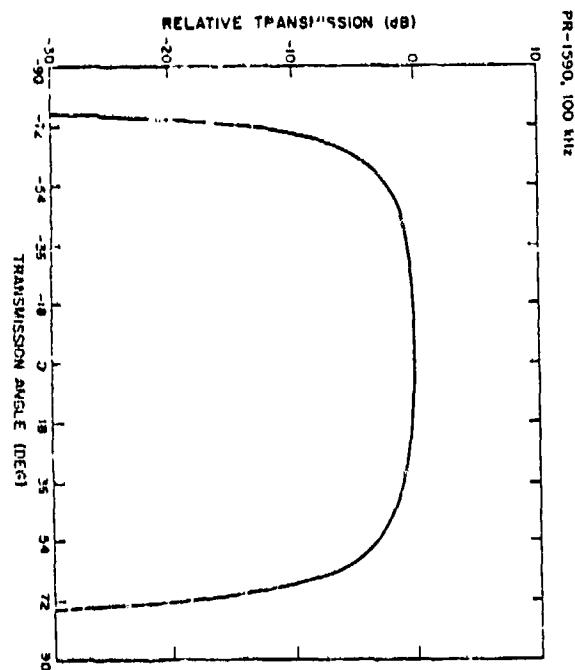
9. Conathane EN-5 Potting Compound

a. *General Information*

Conathane EN-5 is a two-component, liquid polyurethane potting, casting, and molding system. The cured elastomer exhibits outstanding hydrolic stability, stable electrical properties, thermal shock properties, and good handling properties. It is a MOCA-free compound.

b. *Physical Properties* (cured for 7 days at 25°C)

Tensile Strength (MPa) 13.4

Ultimate Elongation (%) 520

Hardness (Shore A) 87

Density (g/cm^3) 0.98

Linear Shrinkage (%) 0.55

Water Absorption (%)
(30-day immersion) 0.48

Fungus Resistance . . . . Non-nutrient

100% Modulus (MPa) (97°C @ 95% RH) . . 5.52

300% Modulus (MPa) (97°C @ 95% RH) . . 8.96

Dielectric Constant at 25°C . . . . . .

   at 1 kHz 3.05
   at 1 MHz 2.87

Volume Resistivity (ohm-cm) . . . . . . 2.1×10^5 @ 25°C

Dielectric Strength (kV/cm r?
0.159-cm thickness) . . . . 240 @ 25°C

c. *Relative transmission loss as a function of incident angle and frequency* (Ref. 40)

Sample Size: 30.48 × 30.48 × 1.85 cm   [see Ref. 41 for measurement technique].
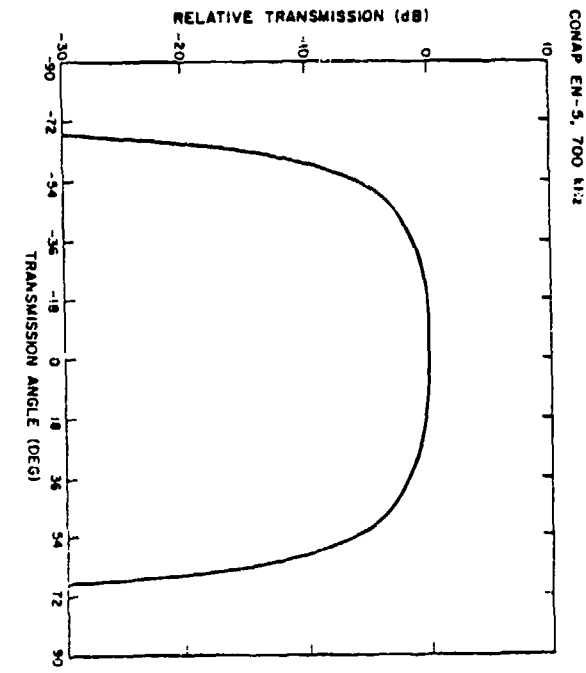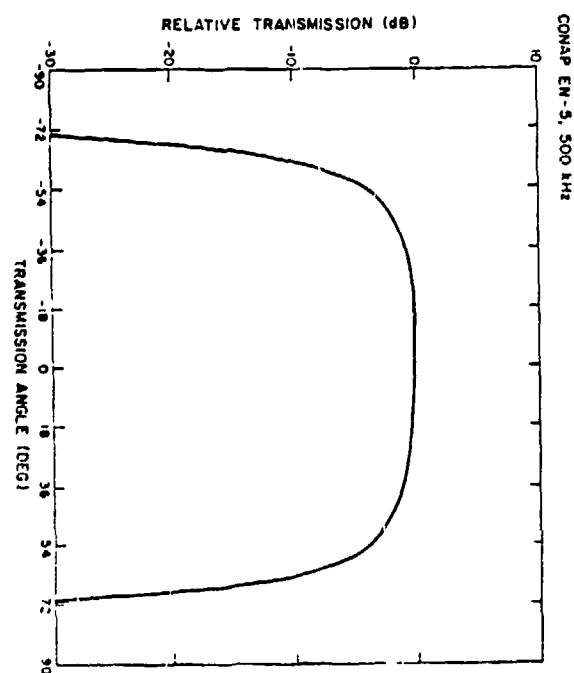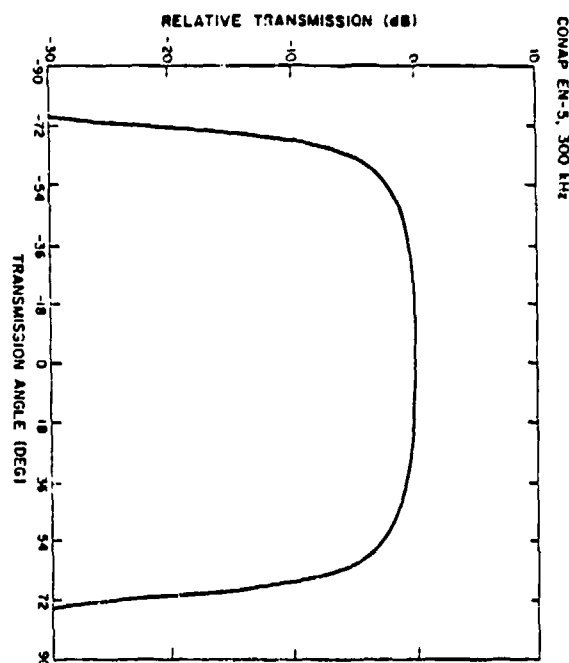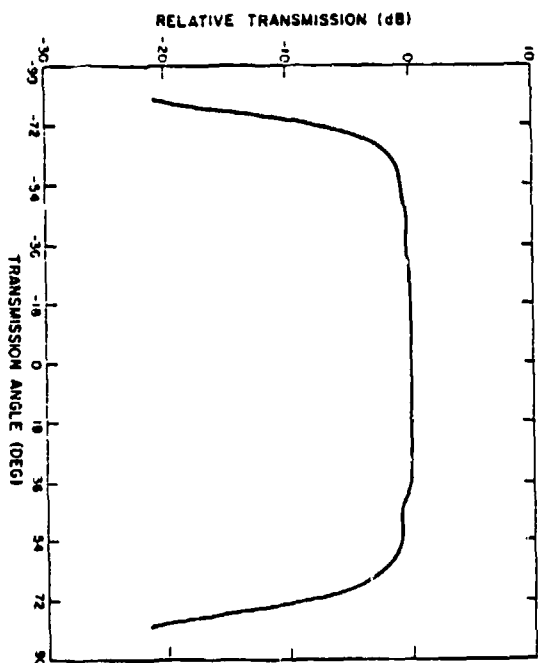
10. <u>Conathane EN-9 Potting Compound</u>

    a. *General Information*

        Conathane EN-9 is a two-component, non-MOCA based, high-strength liquid polyurethane potting and molding system. It was developed specifically to replace MOCA-based systems currently approved under Military Specification MIL-M-24041. It is ozone resistant, has superior hydrolytic stability, low viscosity, high dielectric strength, good thermal shock resistance, and good handling properties.

    b. *Physical Properties* (cured for 16 hrs. at 80°C)

Tensile Strength (MPa) 17.2

Ultimate Elongation (%) . . . . 400 - 500

Hardness (Shore A) . . . . 85 $\pm$ 5

Density (g/cm^3) 1.01

Linear Shrinkage (%) 1

Water Absorption (%)
(25°C after 24 hrs.) 0.20

Ozone resistance (50 pphm) . . . . . . >9 weeks

Fungus Resistance . . . . Non-nutrient

100% Modulus (MPa) . . . . 3.45 - 6.21

300% Modulus (MPa) . . . . 8.28 - 12.8

Dielectric Constant at 25°C:

  at 1 kHz 2.9
  at 1 MHz 2.8

Volume Resistivity (ohm-cm) . . . . . 3.42×10^{15} @ 25°C and 3.15×10^{10} @ 130°C

Dielectric Strength (kV/cm re
0.159-cm thickness) 240

Compression Set (%)
(ASTM D395, Method B) 50

c. *Relative transmission loss as a function of incident angle and frequency* (Ref 40)

Sample Size: 30.48 × 30.48 × 1.64 cm; T = 22.2°C [see Ref. 41 for measurement technique].
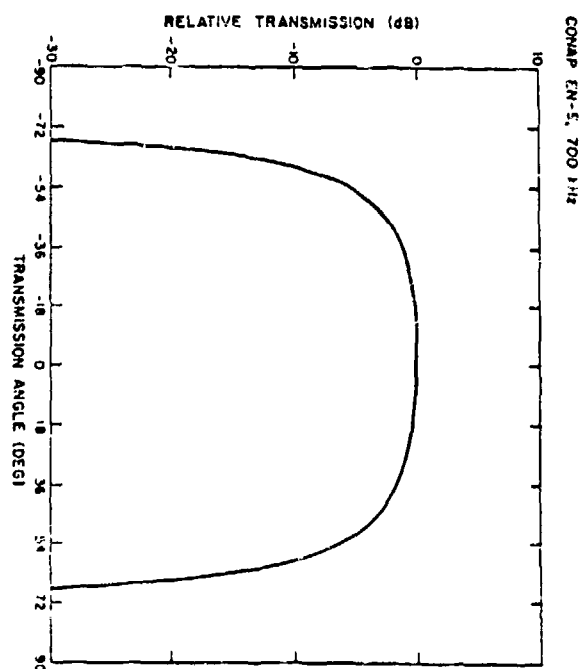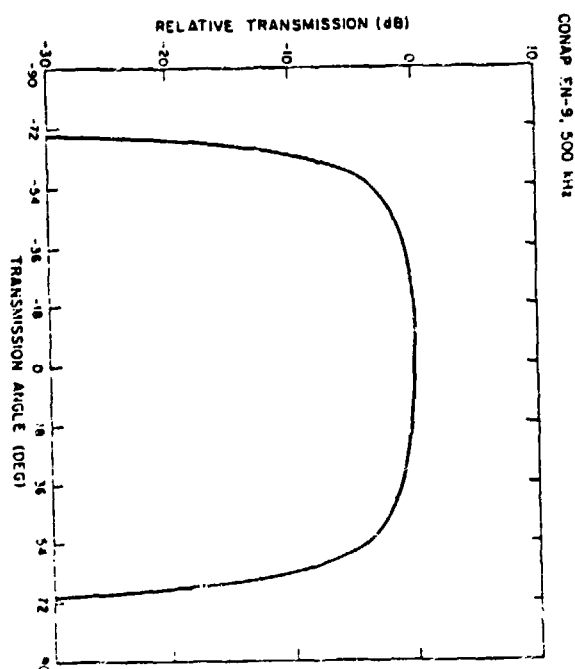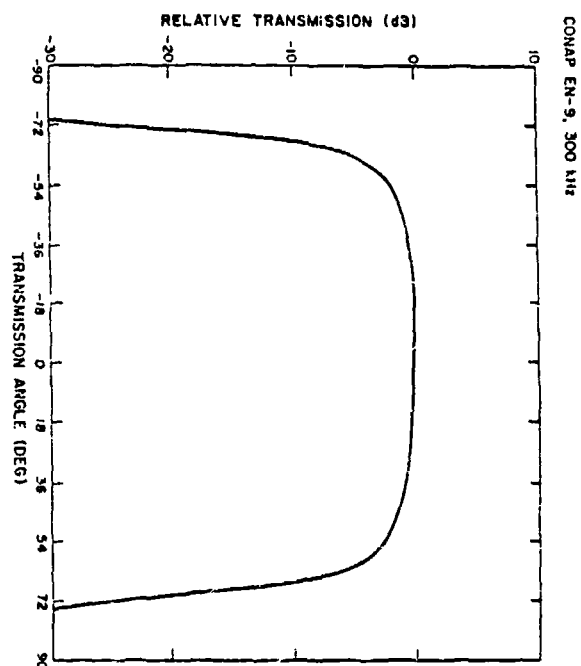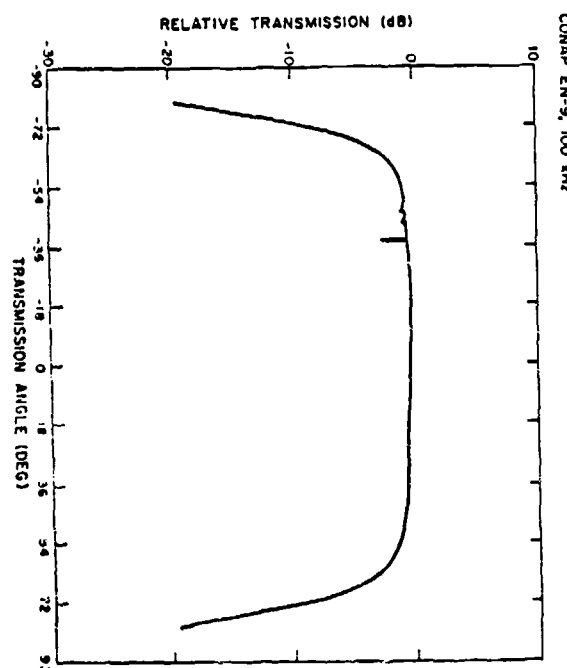
d. *Shear Modulus for EN-9 (Ref. 32)*

$T = 10°C$

157
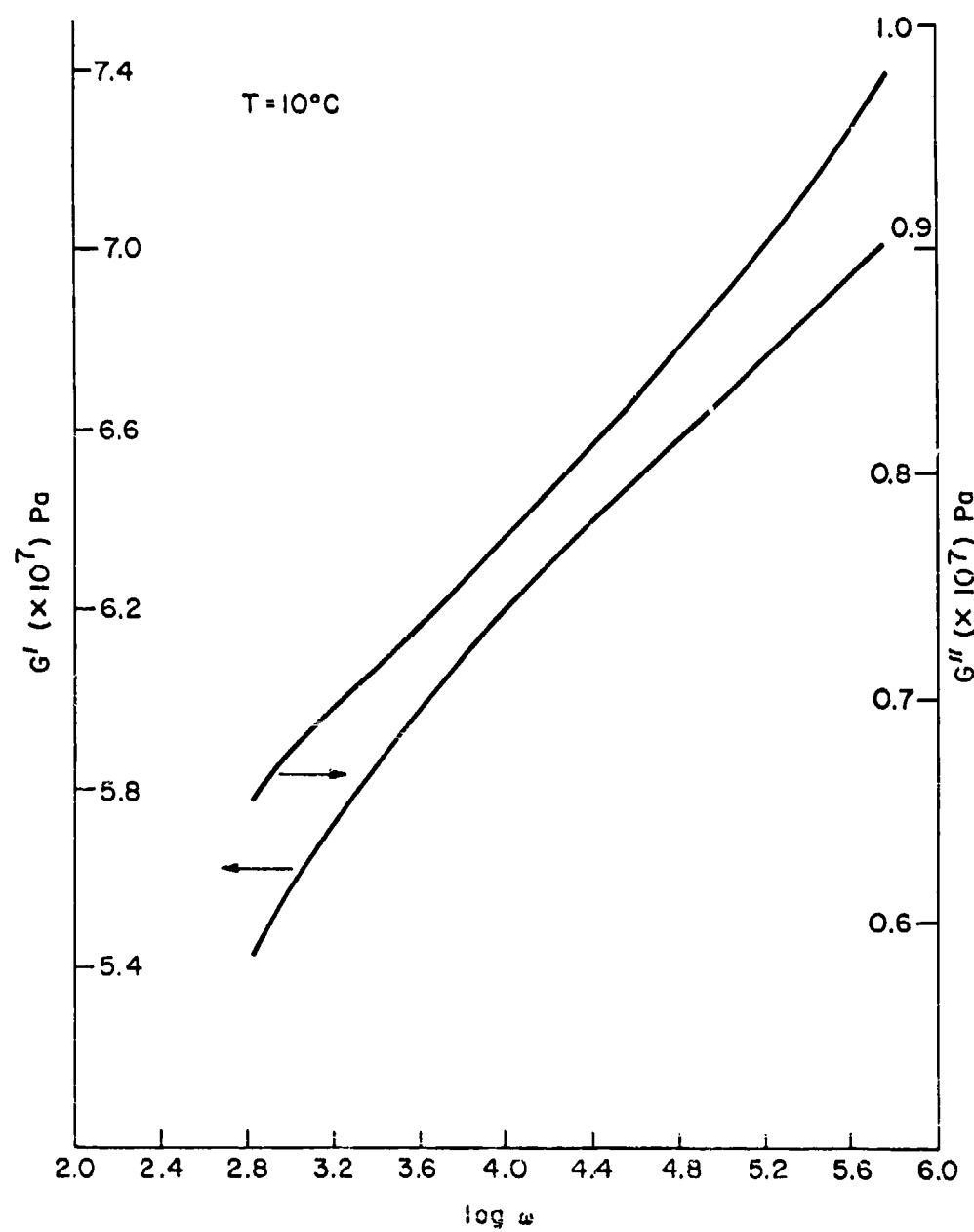
Table 9 - Sound Speeds, Densities, and Characteristic Impedances of Various Metals. (From J.R. Fredrick, "Ultrasonic Engineering," p. 363, John Wiley & Sons, Inc., New York; 1965.)

METALS	SOUND SPEEDS			DENSITY ρ (kg/m^3)	CHARACTERISTIC IMPEDANCE ρc Bulk (kg/m^{2}s)
	LONGITUDINAL		SHEAR		
	BULK m/s	BAR m/s	m/s		
	$\times 10^3$	$\times 10^3$	$\times 10^3$	$\times 10^3$	$\times 10^6$
Aluminum	6.40	5.15	3.13	2.7	17.3
Beryllium	12.89	....	8.88	1.8	23.2
Brass, 70-30	4.37	3.40	2.10	8.5	37.0
Cast Iron	3.50-5.60	3.0-4.7	2.2-3.2	7.2	25.0-40.0
Copper	4.80	3.65	2.33	8.9	42.5
Gold	3.24	2.03	1.20	19.3	63.0
Iron	5.96	5.18	3.22	7.9	46.8
Lead	2.40	1.25	0.79	11.3	27.2
Magnesium	5.74	4.90	3.08	1.7	9.9
Mercury	1.45	....	....	13.6	19.6
Molybdenum	6.25	....	3.35	10.2	63.7
Nickel	5.48	4.70	2.99	8.9	48.5
Platinum	3.96	2.80	1.67	21.4	85.0
Steel, Mild	6.10	5.05	3.24	7.9	46.7
Silver	3.70	2.67	1.70	10.5	36.9
Tin	3.38	2.74	1.61	7.3	24.7
Titanium	5.99	....	3.12	4.50	27.0
Tungsten	5.17	....	2.88	19.3	100.0
Uranium	3.37	....	2.02	18.7	63.0
Zinc	4.17	3.81	2.48	7.1	29.6
Zirconium	4.65	....	2.30	6.4	29.8
Other Solid Materials:					
Crown Glass	5.66	5.30	3.42	2.5	14.0
Granite	....	3.95	....	2.75	....
Ice	3.98	....	1.99	0.9	3.6
Nylon	1.8-2.2	....	....	1.1-1.2	2.0-2.7
Paraffin, Hard	2.2	....	....	0.83	1.8
Plexiglas or Lucite	2.68	1.8	1.32	1.20	3.2
Polystyrene	2.67	....	....	1.06	2.8
Quartz, Fused	5.57	5.37	3.52	2.6	14.5
Teflon	1.35	....	....	2.2	3.0
Tungsten Carbide	6.66	....	3.98	10.0-15.0	66.5-98.5
Wood, Oak	....	4.1	....	0.8	....
Fluids:					
Benzene	1.32	....	....	0.88	1.16
Castor Oil	1.54	....	....	0.95	1.45
Glycerine	1.92	....	....	1.26	2.5
Methyl Iodide	0.98	....	....	3.23	3.2
Oil, SAE 20	1.74	....	....	0.87	1.5
Water, Fresh	1.48	....	....	1.00	1.48

NOTE: These values should be considered as representative only, due to the effects of variations in composition and processing.

IV. TRANSDUCER FILL FLUIDS

A. Introduction

A sonar transducer fill fluid must meet a fairly strict set of requirements--some imposed by the electrical nature of the transducer devices and others caused by the water environment of the transducer. There are also acoustic, long-term stability, compatibility, and handling requirements. With such a diversity of requirements, it is not surprising that compromises have to be made. In the past, there has been a dearth of hard data about the various materials so choices have been based on incomplete or biased information. This section of the handbook discusses the requirements for transducer fill fluids and presents tables of available data for many of the materials in actual or proposed use.

B. Discussion

It is impossible to assign absolute priorities to transducer fill fluids because of the divergence of applications. For example, in a high-frequency transducer, a close acoustic impedance match with seawater may be of paramount importance. In a transducer that unavoidably has narrow crevices, it may be greatly important to use a low-viscosity fluid to avoid entrapping air. For these reasons, Fig. 6 is only a general guide for choosing from among the candidate fluids. The actual values of the boundaries between acceptance and nonacceptance are the result of extensive fill-fluid experience of sonar engineers.

High-volume resistivity is important in order to avoid current leakage. This property may become relatively unimportant for low electrical impedance designs.

Low vapor pressure is necessary to allow vacuum degassing of the fluid.

A relatively low viscosity is desirable in order to avoid air entrainment or entrapment on filling the transducer. For moderately viscous substances, the air-entrapment problem may be lessened if the viscosity decreases upon mild heating.

Good compatibility with the materials in the transducer environment is obviously necessary to assure long life. An acoustic impedance (ρc) match with seawater may be important if the fluid is in the acoustic path and operation at higher frequencies is expected. Low acoustic attenuation (α) is important but usually comes into play only at high frequency.

A low water-solubility limit is necessary in order to resist water permeation. It is also desirable that the solubility of the oil in the water phase be extremely low. Further, it is desirable that the phase diagram for the oil-water-water vapor show a positive deviation from Raoult's law in order to retard water permeation.

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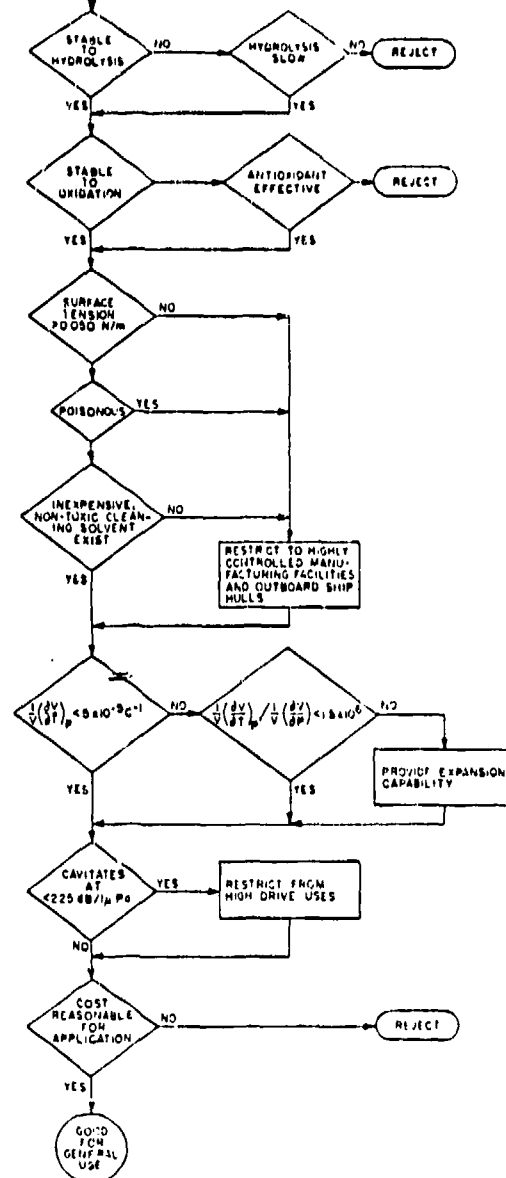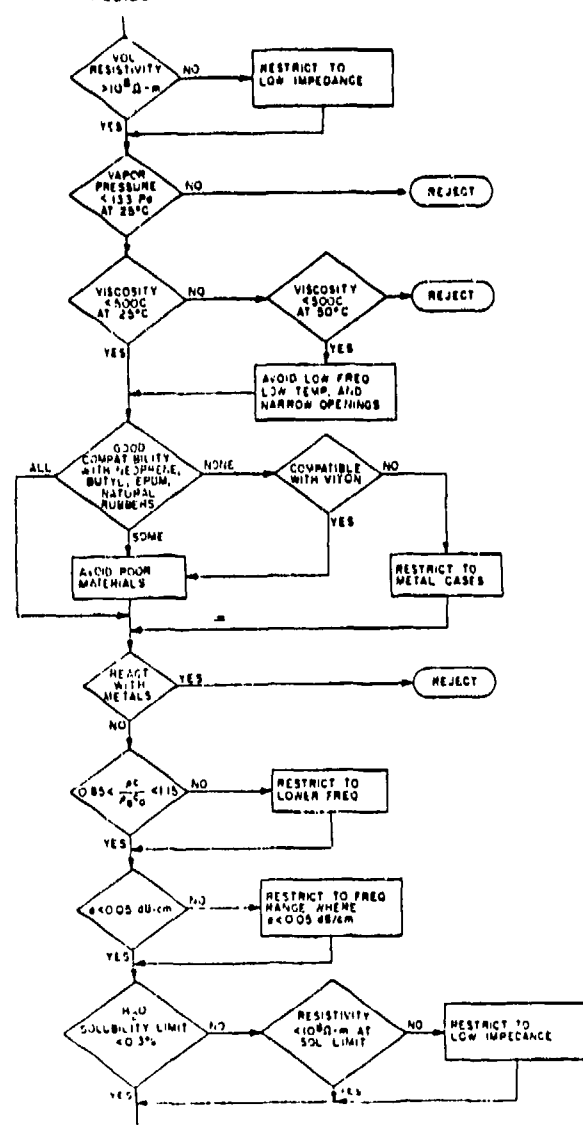
Figure 6 Sonar Transducer Fluid Decision Tree

Stability to hydrolysis and oxidation is important not only to assure constant physical properties but also because the products are frequently much more corrosive than the original fluid.

A high surface tension is important to avoid the oil creeping onto and wetting other surfaces. This has been a recurring problem with various silicone fluids.

Good handling properties such as low toxicity and ease of cleaning are obvious desirable properties.

A low expansion $[(1/V \ (\partial V/\partial T)]$ is necessary in a rigid-cased transducer exposed to a range of temperatures. However, some materials with high thermal expansion also have a high isothermal compressibility $(1/V(\partial V/\partial P))_T$; The ratio of these numbers is a measure of the pressure build-up on warming the transducer.

A high cavitation level is necessary for high-power sources.

Cost reasonableness is difficult to assess. The volume of use is typically very low and cost is of little consequence. In other cases, such as expendable sonobuoys, cost may become a significant factor.

C.   Fill Fluids

The data that follow are taken from a wide variety of sources--including published reports, private communications, manufacturers' literature, and extensive testing at USRD. References are given with each value.

A word is in order about the compatibility results reported here. Long-term compatibility can be only roughly estimated from a short-term test. Additionally, compatibility may be a function of the composition of the material. Care or additional testing is necessary in interpreting these data.

Discrepancies among the values given for surface tension are a result of the different measurement methods employed. Comparisons are possible only with data from the same source.

Remarks about the advantages and disadvantages of each fill fluid are the opinions of the author (C.M. Thompson). Constructive comments about these or any of the data are welcomed.

1.   Castor Oil, Baker DB Grade

Chemical Description: Primarily tri-ester of ricinoleic acid and glycerol;
                         average molecular weight 928 g/mole

Advantages: Good compatibility and acoustic properties.

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Disadvantages: High viscosity, especially at low temperature.

Physical Properties:

Volume Electrical Resistivity (Ω-m): 6×10^{10} [43]

Vapor Pressure (Pa) – Very low [44]

Viscosity (centipoise): 720 at 25°C [43]

Density (kg/m^3): $\rho = 1000/(1.02714 + 7.04\times10^{-4}T + 9.66\times10^{-7}T^2 + 3.0\times10^{-9}T^3$
$-4.91\times10^{-4}P-2.633\times10^{-6}PT-4.04\times10^{-9}PT^2-8.8\times10^{-11}PT^3$
$+1.471\times10^{-6}P^2 + 9.2\times10^{-9}P^2T + 3.6\times10^{-11}P^2T^2-3.63\times10^{-9}P^3$
$-1.66\times10^{-11}P^3T)$ where T is in °C and P is in MPa [45]

Sound Speed (m/s): $1570 (1.000-2.15\times10^{-3}T + 4.0\times10^{-6}T^2 + 2.5\times10^{-6}TP$
$+2.22\times10^{-3}P-3.0\times10^{-6}P^2)$ where T is in °C and P is in MPa [45]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 µPa): 233 [46]

Volume Thermal Expansion (°C^{-1}): 7.34×10^{-4} [44]

Isothermal Compressibility (MPa^{-1}): 47×10^{-6} [47]

Surface Tension (N/m): 0.06736 [44]

Water Solubility Limit: 1.4% at 25°C [44]

Compatibility:

Neoprene W – Good [44]

Neoprene 35003 – Excellent [48]

Butyl B252 – Good [44]

Chlorobutyl H862A – Excellent [48]

Silicone

Polyurethane [49]:

L-100 – Good; L-315 – Excellent; SA-232 – Good

EPDM

Natural 35007 – Excellent [48]

Nitrile

Vitron

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Cork-Rubber composites:

DC-100 – Poor   NC-775 – Poor
DC-116 – Poor   LC-800 – Excellent   [50]
NC-710 – Fair

Adhesives:

EPON VI – Excellent   [44]

Plastics:

"Lexan" Polycarbonate – Excellent   [44]

Syntactic Foam – Excellent   [44]

Vinyl Plastisol Dip Coating – Poor [49]

Metals

Stability [44]:

Oxidation – Reported to polymerize after many years

Hydrolysis – Hydrolyzes slowly

Others [44]:

Toxicity – Very low

Ease of cleanup – Moderately difficult, soluble in acetone, 1:1 methanol,
                  acetone, trichloroethane

Cost – Low

2. Lubricin Castor Oil

Chemical Description: Primarily glyceryl tri-ricinoleate

Advantages: Low viscosity

Disadvantages: Not compatible with many transducer components [51]

Physical Properties:

Volume Electrical Resistivity (Ω-m): 5.2×10^7 Ω-m [52]

Vapor Pressure (Pa)

Viscosity (centipoise): 0.3 Stokes   @ 25°C [51]

Density (kg/m^3)

Sound Speed (m/s): 1519 - 3.18T [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 µPa)

Volume Thermal Expansion ($°C^{-1}$)

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m)

Water Solubility Limit

Compatibility:

  Neoprene W - Poor [51]

  Neoprene 35003

  Butyl (B252) - Good [51]

  Chlorobutyl H862A - Good [51]

  Silicone

  Polyurethane

  EPDM

  Natural 35007 - Poor [51]

  Nitrile

  Viton

  Cork Rubber Composites

  Adhesives:

    Vulcalock - Poor [51]

  Plastics

  Metals

Stability [44]:

  Oxidation

  Hydrolysis - Hydrolyzes slowly

Others [52]:

   Toxicity - Low

   Ease of cleanup

   Cost - Low

3. Tricresyl Phosphate (TCP)

Chemical Description: $(CH_3C_6H_4O)_3PO$

Advantages: Fair acoustic impedance match, high density for covert operation, low viscosity.

Disadvantages: Marginal volume resistivity, compatible with a limited number of elastomers. [44]

Physical Properties:

   Volume Electrical Resistivity (Ω-m): 2×10^8 [54]

   Vapor Pressure (Pa)

   Viscosity (centipoise): 80 at 20°C

   Density (kg/m^3): 1184.2 - 0.83 T [44]

   Sound Speed (m/s): 1586.1 - 3.50 T [53]

   Acoustic Attenuation (dB/cm)

   Cavitation Level (dB/1 μPa)

   Volume Thermal Expansion (°C^{-1}): 6.7×10^{-5} [55]

   Isothermal Compressibility (MPa^{-1})

   Surface Tension (N/m): 0.069 [44]

   Water Solubility Limit: 0.4% @ 25°C [44]

Compatibility:

   Neoprene W - Poor

   Neoprene 5112 - Poor

   Butyl B252 - Good

   Chlorobutyl H862A - Fair

Silicone - Very good

Polyurethane PF 1538 - Poor

EPDM - Fair

Natural (1155) - Poor

Nitrile - Poor

Viton A - Very good

C. S. (BFG35075) - Poor

Cork-Rubber Composites

Adhesives:

  EPON V1 - Good [56]

Plastics: [56]

  "Lexan" Polycarbonate - Poor

  Nylon - Good

  Teflon - Good

Metals: [44]

  Stainless Steel - Very good

  Mild Steel - Fair

  Aluminum - Very good

  Copper - Very good

  Brass - Very good

Stability:

  Oxidation - Good [44]

  Hydrolysis - Good [54]

Others:

  Toxicity - (where ortho isomer has been removed) nontoxic orally not
            an eye or skin irritant, nonflammable [55]

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Ease of cleanup - Soluble in many organic solvents [44]

Cost - Reasonable [55]

4. Polyalkylene Glycol (PAG) Union Carbide LB135Y23

Chemical Discription: Monobutyl Ether of Polypropylene Oxide
Molecular weight, 600 g/mole with small
amounts of the antioxidant dodecyl succinic
anhydride.

Advantages: Cheap, well defined, low thermal expansion [44]

Disadvantages: High water solubility, incompatible with some common
transducer elastomers. [44]

Physical Properties:

Volume Electrical Resistivity (Ω-m): $7.80 \times 10^{10} e^{6.1N}$ (N = mole fraction
of water) [57]

Vapor Pressure (Pa) - Very low [58]

Viscosity (centipoise): $\eta = 190 e^{-0.0513 T}$ [58]

Density (kg/m^3): $996.2 - 1.1 T + 6.2 \times 10^{-3} T^2$ [57]

Sound Speed (m/s): $1395 - 3.34 T$ [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 μPa) - Threshold at 240; quickly falls to 227 [46]

Volume Thermal Expansion ($^\circ C^{-1}$)

Isothermal Compressibility (MPa^{-1}): 2.22×10^{-10} [57]

Surface Tension (N/m): 0.063 [44]

Water Solubility Limit

Compatibility: [57]

Neoprene W - Fair

Neoprene FG 35007 - Poor

Butyl B252 - Very good

Chlorobutyl H862A - Very good

Silicone V121 - Very good

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Polyurethane PRC-1538 - Poor

EPDM Nordel 1070 - Poor

Natural BFG 35007 - Poor

Nitrile - Very good

Viton - Good

CTBN (BFG 35075) - Poor

Natural (BFG 35001) - Poor

Cork-Rubber Composites [50]:

   DC-100 - Poor
   NC-710 - Poor
   NC-775 - Fair
   LC-800 - Fair

Adhesives

Plastics

Metals

Stability [57]:

Oxidation - Good

Hydrolysis - Very good

Others:

Toxicity - Nontoxic, no eye or skin irritations [57]

Ease of cleanup - Readily removed from surfaces with acetone, acetone-alcohol, or methylethyl ketone. [57]

Cost - Low [44]

5. Dow Chemical Co. P4000 Polyglycol

Chemical Description: A polypropylene oxide with alcohol end groups and molecular weight of about 4000 g/mole

Advantages: High viscosity where required.

Disadvantages: Low oxidative stability.

Physical Properties:

Volume Electrical Resistivity (Ω-m)

Vapor Pressure (Pa)

Viscosity (centipoise): 854 @ 25°C [59]

Density (kg/m^3): 1005 @ 25°C [59]

Sound Speed (m/s)

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 μPa)

Volume Thermal Expansion (°C^{-1})

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m): 0.0322 @ 25°C [59]

Water Solubility Limit

Compatibility: [60]

  Neoprene W - Fair

  Neoprene 5109 - Very good

  Butyl B252 - Good

  Chlorobutyl

  Silicone (V121) - Good

  Polyurethane

  EPDM

  Natural 35007

  Nitrile 6100 - Good

  Viton

  Cork-Rubber Composites

  Adhesives

  Plastics

  Metals

Stability:

  Oxidation - Stable only if used with an oxidation inhibitor [59]

  Hydrolysis

Others:

  Toxicity

  Ease of cleanup - Soluble in methylethyl ketone, trichloroethane,
                alcohols [60]

  Cost - 70 cents/pound [60]

6. Dow Chemical Co. 112-2 Polyglycol

Chemical Description: A poly(propylene-ethylene) oxide initiated with
                   glycerol. Molecular weight $\sim$ 4500 g/mole [59]

Advantages: High viscosity were required. [44]

Disadvantages: Low oxidative stability.

Physical Properties:

  Volume Electrical Resistivity (Ω-m)

  Vapor Pressure (Pa)

  Viscosity (centipoise): 674 @ 25°C [59]

  Density (kg/m^3): 1023 @ 25°C [59]

  Sound Speed (m/s)

  Acoustic Attenuation (dB/cm)

  Cavitation Level (dB/1 μPa)

  Volume Thermal Expansion (°C^{-1})

  Isothermal Compressibility (MPa^{-1})

  Surface Tension (N/m)

  Water Solubility Limit: <0.1% [59]

  Compatibility: [60]

    Neoprene W - Fair

Neoprene 5109 — Good

Butyl B252 — Good

Chlorobutyl

Silicone (V121) — Very good

Polyurethane (PRC 1538) — Poor

EPDM

Natural 35007

Nitrile

Viton

Cork-Rubber Composites

Adhesives

Plastics

  "Lexan" Polycarbonate — Excellent

Metals

Stability:

Oxidation — Stable only if used with an oxidation inhibitor [59]

Hydrolysis

Others:

Toxicity — Nontoxic, presents no unusual handling hazards. [59]

Ease of cleanup — Soluble in methylethylketone, trichloroethane, alcohols [60]

Cost — ∿70 cents/pound [60]

7. Dow Corning 200.5 Silicone

Chemical Description: Polydimethylsiloxane

Advantages: Good compatibility

Disadvantages: Low sound speed, troublesome handling properties, slight volatility

Physical Properties:

  Volume Electrical Resistivity (Ω-m)

  Vapor Pressure (Pa): 0.004 @ 70°C [61]

  Viscosity (centipoise): 4.8 @ 25°C [61]

  Density (kg/m^3): 920 @ 25°C [61]

  Sound Speed (m/s): 1049 - 3.05 T [53]

  Acoustic Attenuation (dB/cm) - Measurable only at high frequency [58]

  Cavitation Level (dB/1 μPa)

  Volume Thermal Expansion (°C^{-1}): 0.00105 [61]

  Isothermal Compressibility (MPa^{-1})

  Surface Tension (N/m): 0.0197 @ 25°C [61]

  Water Solubility Limit

  Compatibility:

    Neoprene W

    Neoprene 35003

    Butyl B252

    Chlorobutyl

    Silicone

    Polyurethane

    EPDM

    Natural 35007

    Nitrile

    Viton

    Cork-Rubber Composites

    Adhesives

    Plastics

Metals

Stability:

  Oxidation - Good [61]

  Hydrolysis

Others:

  Toxicity - Nontoxic and nonirritating [61]

  Ease of cleanup - Soluble in methylethylketone, ethyl ether, carbon
                    tetrachloride, toluene, trichloroethane, turpentine,
                    xylene [61]. Some difficulties reported. [44]

Cost - Moderate

8. Dow Corning 200.20 Silicone

Chemical Description: Polydimethylsiloxane

Advantages: Good compatibility

Disadvantages: Low sound speed, troublesome handling properties.

Physical Properties:

  Volume Electrical Resistivity (Ω-m)

  Vapor Pressure (Pa) - Very low [66]

  Viscosity (centipoise): 19 at 25°C [61]

  Density (kg/m^3): 949 at 25°C [61]

  Sound Speed (m/s): 1065 - 293 T [53]

  Acoustic Attenuation (dB/cm) - Measurable only at high frequency [58]

  Cavitation Level (dB/1 µPa)

  Volume Thermal Expansion (°C^{-1}): 0.00107 [61]

  Isothermal Compressibility (MPa^{-1})

  Surface Tension (N/m): 0.0206 @ 25°C [61]

  Water Solubility Limit

  Compatibility:

173

Neoprene W

Neoprene 35003

Butyl B252

Chlorobutyl H862A

Silicone

Polyurethane

EPDM

Natural 35007

Nitrile

Viton

Cork-Rubber Composites

Adhesives

Plastics

Metals

Stability:

Oxidation - Good [61]

Hydrolysis

Others:

Toxicity - Nontoxic eye irritant [61]

Ease of cleanup - Soluble in methylethylketone, ethyl ether, carbon tetrachloride, toluene, trichloroethane, turpentine, xylene. [61] Some difficulties reported.[44]

Cost - Moderate

9. Dow Corning 200.100 Silicone

Chemical Description: Polydimethylsiloxane

Advantages: Good compatibility

Disadvantages: Low sound speed, troublesome handling properties

Physical Properties:

Volume Electrical Resistivity (Ω-m)

Vapor Pressure (Pa): Very low [61]

Viscosity (centipoise):   96 @ 25°C [61]

Density (kg/m^3): 984.4 - 0.88 T [44]

Sound Speed (m/s): 1073 - 2.87 T [53]

Acoustic Attenuation (dB/cm) - Measurable only at high frequency [58]

Cavitation Level (dB/1 µPa)

Volume Thermal Expansion (°C^{-1}): 0.00096 [61]

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m): 0.0209 @ 25°C [61]

Water Solubility Limit

Compatibility:

Neoprene W

Neoprene 35003

Butyl B252

Chlorobutyl H862A

Silicone

Polyurethane

EPDM

Natural 35007

Nitrile

Viton

Cork-Rubber Composites [50]:
   DC-100 - Fair
   NC-710 - Fair
   LC-800 - Fair
Adhesives
Plastics

175

Metals

Stability:

  Oxidation - Good [61]

  Hydrolysis

Others:

  Toxicity - Nontoxic eye irritant [61]

  Ease of cleanup - Soluble in methylethylketone, ethyl ether, carbon
                    tetrachloride, toluene, trichloroethane, turpentine,
                    xylene. [61] some difficulties reported. [44]

  Cost - Moderate

10. Dow Corning 200.1000 Silicone

Chemical Description: Polydimethylsiloxane

Advantages: Good Compatibility

Disadvantages: Low sound speed, troublesome handling properties

Physical Properties:

  Volume Electrical Resistivity (Ω-m)

  Vapor Pressure (Pa) - Very low [61]

  Viscosity (centipoise):   971 @ 25°C [61]

  Density (kg/m^3):   972 @ 25°C [61]

  Sound Speed (m/s):   1074 - 2.75 T [53]

  Acoustic Attenuation (dB/cm) - Measurable only at high frequency [58]

  Cavitation Level (dB/1 µPa)

  Volume Thermal Expansion (°C^{-1}):   0.00096 [61]

  Isothermal Compressibility (MPa^{-1})

  Surface Tension (N/m):   0.0212 @ 25°C [61]

  Water Solubility Limit

Compatibility:

  Neoprene W

Neoprene 35003

Butyl B252

Chlorobutyl H862A

Silicone

Polyurethane

EPDM

Natural 35007

Nitrile

Viton

Cork-Rubber Composites

Adhesives

Plastics

Metals

Stability:

Oxidation - Good [61]

Hydrolysis

Others:

Toxicity - Nontoxic eye irritant [61]

Ease of cleanup - Soluble in methylethylketone, ethyl ether, carbon
tetrachloride, toluene, trichloroethane, turpentine,
xylene. [61]   Some difficulties reported. [44]

Cost - Moderate

11. Dow Corning 220 Silicone

Chemical Description: A mixture of low and high molecular weight
polydimethylisiloxanes

Advantages: Good compatibility

Disadvantages: Low sound speed, troublesome handling properties. Reported
to fractionate under vacuum. [44]

Physical Properties:

Volume Electrical Resistivity (Ω-m)

Vapor Pressure (Pa)

Viscosity (centipoise)

Density (kg/m^3):   1043.1 - 0.80 T [51]

Sound Speed (m/s):   1258 - 3.04 T [53]

Acoustic Attenuation (dB/cm) - Measurable only at high frequency. [58]

Cavitation Level (dB/1 μPa)

Volume Thermal Expansion (°C^{-1})

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m)

Water Solubility Limit

Compatibility:

Neoprene W

Neoprene 35003

Butyl B252

Chlorobutyl H862A

Silicone

Polyurethane

EPDM

Natural 35007

Nitrile

Viton

Cork-Rubber Composites

Adhesives

Plastics

Metals

178

Stability:

Oxidation

Hydrolysis

Others:

Toxicity - Nontoxic, eye irritant [61]

Ease of cleanup - Some difficulties reported [44]

Cost - Moderate

12. Dow Corning DC 510/100 Silicone

Chemical Description: Polymethylphenylsiloxane

Advantages:

Disadvantages:

Physical Properties:

Volume Electrical Resistivity (Ω-m): 20×10^{12} [58]

Vapor Pressure (Pa)

Viscosity (centipoise): 99.2 @ 25°C [58]

Density (kg/m^3): 1006.6 - 0.87 T [44]

Sound Speed (m/s)

Acoustic Attenuation (dB/cm) - Measurable loss above 50 kHz [58]

Cavitation Level (dB/1 μPa) - Cavitates at 1/3 intensity of water [58]

Volume Thermal Expansion (°C^{-1})

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m)

Water Solubility Limit

Compatibility:

Neoprene W

Neoprene 35003

Butyl B252

Chlorobutyl H862A

Silicone

Polyurethane

EPDM

Natural 35007

Nitrile

Viton

Cork-Rubber Composites

Adhesives

Plastics

Metals

Stability:

Oxidation

Hydrolysis

Others:

Toxicity - Skin and eye irritant [58]

Ease of cleanup - Some difficulties reported [58]

Cost - High

13. <u>SF1147 Methyl Alkyl Silicone, General Electric Co.</u>

Chemical Discription: Polymethylalkylsiloxane

Advantages:

Disadvantages:

Physical Properties:

Volume Electrical Resistivity (Ω-m): 3×10^{13} [62]

Vapor Pressure (Pa)

Viscosity (centipoise): 44.5 @ 25°C [63]

Density (kg/m^3): 890 @ 25°C [63]

Sound Speed (m/s): 1356.6 − 3.29 T [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 µPa)

Volume Thermal Expansion (°C^{-1}): 7×10^{-4} [63]

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m): 0.0455 @ 25°C [63]

Water Solubility Limit: <0.05% [63]

Compatibility:

  Neoprene W − Good [44]

  Neoprene 35003

  Butyl B252 − Fair [44]

  Chlorobutyl H862A

  Silicone − Good [63]

  Polyurethane − Excellent [44]

  EPDM

  Natural 35007

  Nitrile

  Viton − Good [62]

  Cork-Rubber Composites

  Adhesives

  Plastics

  Metals:

    Silver − Very good
    Copper − Very good
    Aluminum − Very good [63]
    350 Stainless Steel − Very good

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Stability:

  Oxidation - Excellent [63]

  Hydrolysis - Excellent [44]

Others:

  Toxicity - Low, nontoxic orally, nonskin irritating, slight temporary
            eye irritant. [63]

  Ease of cleanup - Can be cleaned with common solvents - acetone, trichloro-
            ethane. [44]

  Cost - Very high [63]

14. Dow Corning FS-1265 Silicone

Chemical Description: Fluorosilicone

Advantages: Compatible with many materials, low viscosity.

Disadvantages: Very expensive, poor acoustic impedance match.

Physical Properties:

  Volume Electrical Resistivity (Ω-m)

  Vapor Pressure (Pa)

  Viscosity (centipoise):   375 @ 25°C [61]

  Density (kg/m^3):   1250 @ 25°C [64]

  Sound Speed (m/s):   1015 @ 25°C [53]

  Acoustic Attenuation (dB/cm)

  Cavitation Level (dB/1 μPa)

  Volume Thermal Expansion (°C^{-1}): 9.49×10^{-4} [64]

  Isothermal Compressibility (MPa^{-1})

  Surface Tension (N/m):   0.0257 [61]

  Water Solubility Limit

  Compatibility:

  Neoprene W

Neoprene 35003

Butyl B252 - Good [64]

Chlorobutyl H862A

Silicone

Polyurethane

EPDM

Natural 35007

Nitrile

Viton - Good [64]

Teflon - Good [64]

Cork- Rubber Composites

Adhesives

Plastics

Metals

Stability:

Oxidation - Excellent [64]

Hydrolysis

Others:

Toxicity - Essentially nontoxic except at temperatures > 550°F at which
point toxic vapors may be evolved. [64]

Ease of cleanup - Soluble in ketones, methylene chloride. [64]

Cost - Very high

15. Isopar L (Exxon Company)

Chemical Description: A narrow-boiling fraction of highly-branched, saturated
hydrocarbons, average molecular weight 171 g/mole.

Advantages: Buoyant [44]

Disadvantages: Incompatible with many materials. [44]

Physical Properties:

Volume Electrical Resistivity (Ω-m)

Vapor Pressure (Pa): 4.1×10^3 @ 38°C [35]

Viscosity (centipoise): 2.87 @ 0°C [65]

Density (kg/m^3): 777.5 - 0.74 T [65]

Sound Speed (m/s): 1342 - 4.0 T [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 μPa)

Volume Thermal Expansion (°C^{-1})

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m): 0.0231 @ 25°C [65]

Water Solubility Limit: 0.01% [65]

Compatibility:

Neoprene W

Neoprene 35003

Butyl B252

Chlorobutyl H862A

Silicone

Polyurethane

EPDM

Natural 35007

Nitrile

Viton

Cork-Rubber Composites

Adhesives

Plastics

Metals

Stability:

  Oxidation

  Hydrolysis

Others:

  Toxicity - Possible toxicity. Skin irritant. [65]

  Ease of cleanup

  Cost

16. Isopar M (Exxon Company)

Chemical Description: A narrow-boiling fraction of highly-branched saturated
                       hydrocarbons, average molecular weight 191 g/mole.

Advantages: Buoyant [44]

Disadvantages: Incompatible with many materials. [44]

Physical Properties:

  Volume Electrical Resistivity (Ω-m)

  Vapor Pressure (Pa): 4.1×10^3 [66]

  Viscosity (centipoise): 2.46 @ 25°C [66]

  Density (kg/m^3): 789.0 - 0.72 T [56]

  Sound Speed (m/s): 1359 - 3.9 T [53]

  Acoustic Attenuation (dB/cm)

  Cavitation Level (dB/1 µPa)

  Volume Thermal Expansion (°C^{-1})

  Isothermal Compressibility (MPa^{-1})

  Surface Tension (N/m): 0.0248 @ 25°C [66]

  Water Solubility Limit: 0.01% [66]

  Compatibility:

    Neoprene 5109 - Fair [44]

    Neoprene 35003

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Butyl B252

Chlorobutyl H862A - Poor [44]

Silicone (V121) - Poor

Polyurethane (PRC1538) - Fair [44]

EPDM Nordel 1070 - Poor [44]

Natural 1155 - Poor [44]

Nitrile 6100 - Good [44]

Viton

CTBN (BFG 35075) - Poor [44]

Cork-Rubber Composites:

  DC-100 - Poor
  LC-800 - Poor [44]
  NC-775 - Good

Adhesives:

  EPON IV - Good [56]

Plastics:

  Syntactic Foam - Good [56]
  Tygon Tubing - Poor [44]

Metals

Stability:

  Oxidation

  Hydrolysis

Others:

  Toxicity - Possible inhalation toxicity. Skin and eye irritant. [66]

  Ease of cleanup

  Cost

17. Norpar 12

Chemical Description: Narrow-boiling, normal paraffinic petroleum distillate. Average molecular weight, 163 g/mole. [67]

Advantages: Buoyant [44]

Disadvantages: Incompatible with many materials.

Physical Properties:

Volume Electrical Resistivity (Ω-m)

Vapor Pressure (Pa): 5500 @ 38°C [65]

Viscosity (centipoise): 1.26 @ 15.6°C [65]

Density (kg/m^3): 758.8 - 0.72 T [44]

Sound Speed (m/s): 1264 @ 26°C [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 μPa)

Volume Thermal Expansion (°C^{-1})

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m): 0.0248 [65]

Water Solubility Limit

Compatibility:

Neoprene W

Neoprene 35003

Butyl B252

Chlorobutyl H862A

Silicone

Polyurethane

EPDM

Natural 35007

Nitrile

187

Viton

Cork-Rubber Composites

Adhesives

Plastics

Metals

Stability:

Oxidation

Hydrolysis

Others:

Toxicity - Inhalation TLV: 300 ppm - Acute Oral LD_{50} (Rat):
>5 g/kg - Acute Dermal LD_{50} (Rabbit): 5 ml/kg. [67]

Ease of cleanup

Cost

18.   Shell Sol 71 (Shell Chemical Co.)

Chemical Description: A petroleum distillate containing 95.9% saturated
hydrocarbons and 4.1% olefins.

Advantages: Buoyant

Disadvantages: Incompatible with many materials.

Physical Properties:

Volume Electrical Resistivity (Ω-m)

Vapor Pressure (Pa):   ~700 [68]

Viscosity (centipoise)

Density (kg/m^3):   756. @ 16°C

Sound Speed (m/s):   1216 @ 26°C [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 µPa)

Volume Thermal Expansion (°C^{-1})

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m): 0.0644 [44]

Water Solubility Limit

Compatibility:

  Neoprene W

  Neoprene 35003

  Butyl B252

  Chlorobutyl H862A

  Silicone

  Polyurethane

  EPDM

  Natural 35007

  Nitrile

  Viton

  Cork-Rubber Composites

  Adhesives

  Plastics

  Metals

Stability:

  Oxidation

  Hydrolysis

Others:

  Toxicity

  Ease of cleanup

  Cost

19. Polyalphaolefin (PAO) (Uniroyal PAO-20E)

Chemical Description: A polymer of 1-octene, molecular weight, 1015 g/mole.

Advantages: High resistivity, low water solubility. [44]

Disadvantages: Incompatible with most rubbers. Moderately high viscosity. [44]

Physical Properties:

Volume Electrical Resistivity (Ω-m): 1×10^{15} [69]

Vapor Pressure (Pa) - Very low [69]

Viscosity (centipoise): 548 @ 21°C [69]

Density (kg/m^3): 856.0 - 0.63 T [56]

Sound Speed (m/s): 1532 - 3.6 T [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 μPa)

Volume Thermal Expansion (°C^{-1}): 7.5×10^{-4} [69]

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m)

Water Solubility Limit: 0.002% [44]

Compatibility:

Neoprene W - Poor

Neoprene 35003

Butyl B252 - Poor

Chlorobutyl H862A - Poor

Silicone (V121) - Very good

Polyurethane (PRC 1538) - Marginal [44]

EPDM - Poor

Natural (BFG 35007) - Poor

Nitrile (BUNAN) - Fair

Viton - Good

Butyl (70821) - Poor [58]

CTBN (BF 635075) - Poor [44]

Cork-Rubber Composites

Adhesives

Plastics:

   "Lexan" (Polycarbonate) - Excellent [44]

Metals

Stability:

  Oxidation - Excellent [44]

  Hydrolysis - Excellent [44]

Others:

  Toxicity - Nontoxic, LD50>40ml/kg [69]

  Ease of cleanup - Moderate, soluble in petroleum ether, trichloroethane
            [44]

  Cost - Low [44]

          20.   Robane, Robeco Chemical Company

Chemical Description: Squalane - $C_{30}H_{62}$ - 2,6,10,15,19,23 Hexamethyltetra-
                        cosane. [70]

Advantages: Buoyant

Disadvantages:

Physical Properties:

  Volume Electrical Resistivity (Ω-m): 3.30×10^{12} [52]

  Vapor Pressure (Pa)

  Viscosity (centipoise)

  Density (kg/m^3):   809 @ 24°C [70]

  Sound Speed (m/s):   1467 - 3.62 T [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 μPa)

Volume Thermal Expansion ($°C^{-1}$)

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m)

Water Solubility Limit

Compatibility:

  Neoprene W – Excellent [52]

  Neoprene 35003

  Butyl B252 – Fair [52]

  Chlorobutyl H862A – Good [52]

  Silicone

  Polyurethane

  EPDM

  Natural BFG 35007 – Poor [52]

  Nitrile

  Viton

  Cork-Rubber Composites

  Adhesives

  Plastics

  Metals

 Stability:

  Oxidation – Excellent [70]

  Hydrolysis

 Others:

  Toxicity

Ease of cleanup – Soluble in hydrocarbons [44]

Cost

21. Robuoy, Robeco Chemical Company

Chemical Description: $C_{19}H_{40}$ – 2,6,10,14 – tetramethylpentadecane

Advantages: Buoyant

Disadvantages:

Physical Properties:

Volume Electrical Resistivity (Ω-m): 7.30×10^{11} [52]

Vapor Pressure (Pa)

Viscosity (centipoise): 5.0 @ 25°C [70]

Density (kg/m^3): 780 @ 24° [52]

Sound Speed (m/s): 1403 – 3.49 T [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 μPa)

Volume Thermal Expansion ($°C^{-1}$)

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m): 0.0255 [70]

Water Solubility Limit

Compatibility:

Neoprene W – Very good [52]

Neoprene 35003

Butyl B252 – Poor [52]

Chlorobutyl H862A – Fair [52]

Silicone

Polyurethane

EPDM

Natural 35007 - Poor [52]

Nitrile

Viton

Cork-Rubber Composites

Adhesives

Plastics

Metals

Stability:

Oxidation - Excellent [70]

Hydrolysis

Others:

Toxicity - Nontoxic [70]

Ease of cleanup - Soluble in hydrocarbons [44]

Cost

22. Transformer Oil, Texaco No. 55

Chemical Description: Unknown

Advantages:

Disadvantages:

Physical Properties:

Volume Electrical Resistivity (Ω-m)

Vapor Pressure (Pa)

Viscosity (centipoise)

Density (kg/m^3): 902 @ 0°C [56]

Sound Speed (m/s): 1507.5 - 3.73 T [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dE/1 µPa)

Volume Thermal Expansion ($°C^{-1}$)

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m)

Water Solubility Limit

Compatibility:

  Neoprene W

  Neoprene 35003

  Butyl B252

  Chlorobutyl H862A

  Silicone

  Polyurethane

  EPDM

  Natural 35007

  Nitrile

  Viton

  Cork-Rubber Composites

  Adhesives

  Plastics

  Metals

Stability:

  Oxidation

  Hydrolysis

Others:

  Toxicity

  Ease of cleanup

  Cost

23. Motor Oil, Cam 2, 20W-50 Viscosity

Chemical Description:

Advantages: Easily available

Disadvantages: Presumably a low viscosity change with temperature [53]

Physical Properties:

Volume Electrical Resistivity (Ω-m)

Vapor Pressure (Pa)

Viscosity (centipoise)

Density (kg/m^3)

Sound Speed (m/s): $1538 - 3.68$ T [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 μPa)

Volume T... Expansion ($°C^{-1}$)

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m)

Water Solubility Limit

Compatibility:

Neoprene W

Neoprene 35003

Butyl B252

Chlorobutyl H862A

Silicone

Polyurethane

EPDM

Natural 35007

Nitrile

Viton

Cork-Rubber Composites

Adhesives

Plastics

Metals

Stability:

Oxidation

Hydrolysis

Others:

Toxicity

Ease of cleanup

Cost

24. Fluorinert, FC 75, 3M Co.

Chemical Description: Fluorinated hydrocarbon, molecular weight, 290 g/mole.

Advantages: Relatively inert

Disadvantages: Expensive, high density

Physical Properties:

Volume Electrical Resistivity (Ω-m): 8×10^{15} @ 25°C [71]

Vapor Pressure (Pa): 4.1×10^3 [71]

Viscosity (centipoise): 1.41 @ 25°C [71]

Density (kg/m^3): 1760.0 @ 25°C [71]

Sound Speed (m/s): 656.0 − 2.86 T [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 μPa)

Volume Thermal Expansion (°C^{-1}): 0.0016 [71]

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m): 0.015 [71]

Water Solubility Limit

Compatibility:

Neoprene W

Neoprene 35003

Butyl B252

Chlorobutyl H862A

Silicone

Polyurethane

EPDM

Natural 35007

Nitrile

Viton

Cork-Rubber Composites

Adhesives

Plastics

Metals

Stability:

Oxidation

Hydrolysis

Others:

Toxicity

Ease of cleanup

Cost - High

25. Fluorolube, FS-5, Hooker Chemical Co.

Chemical Description: Perfluorinated hydrocarbon

Advantages:

Disadvantages:

Physical Properties:

Volume Electrical Resistivity (Ω-m)

Vapor Pressure (Pa)

Viscosity (centipoise)

Density (kg/m^3): 1933.8 - 1.71 T [72]

Sound Speed (m/s): 953 - 2.63 T [53]

Acoustic Attenuation (dB/cm)

Cavitation Level (dB/1 μPa)

Volume Thermal Expansion ($^\circ$C^{-1})

Isothermal Compressibility (MPa^{-1})

Surface Tension (N/m)

Water Solubility Limit

Compatibility:

Neoprene W

Neoprene 35003

Butyl B252

Chlorobutyl H862A

Silicone

Polyurethane

EPDM

Natural 35007

Nitrile

Viton

Cork-Rubber Composites

Adhesives

Plastics

Metals

Stability:

Oxidation

Hydrolysis

Others:

Toxicity

Ease of cleanup

Cost

V. BONDING OF ELASTOMERS TO METAL

A. Factors Involved in Elastomer-to-Metal Bonds

It is possible to bond most elastomers by some means to practically all of the common metals. The choice of the elastomer to be used is an important factor in the design of a bonded assembly with elastomeric materials. Natural rubber (NR), styrene-butadiene rubber (SBR), chloroprene (Neoprene) and nitrile rubber (NBR) are used most often in bonded elastomer parts. Butyl rubber (IIR), polybutadiene (BR), fluorocarbon rubbers (CFM), EPM, EPDM, polyurethane, polyacylates, and silicone rubbers are used to a smaller extent. Silicone rubbers, in particular, are relatively difficult to bond to metals.

A number of adhesives or adhesive systems are commercially available for bonding practically all available elastomers. The final selection of an adhesive should be based on its intended service application and the recommendations of the manufacturer. However, there are a number of general characteristics that an adhesive should possess in order to form a successful elastomer-to-metal bond [73].

The adhesive should readily wet the metal surface. It should be able to displace and absorb a reasonable amount of surface contamination from the metal or elastomer as well as any compounding ingredients that might migrate to the surface of the elastomer. Waxy materials, which may have been added to the rubber for antioxidation purposes, and plasticizers are particularly troublesome. The adhesive should be able to accommodate the wide variations in cure conditions used to vulcanize

different elastomer compounds. It should have a sufficient amount of cohesion to resist sweeping in the uncured state. It should retain its desired properties in a variety of service situations and be able to maintain bond integrity throughout any chemical or mechanical post-bonding treatment. Most important, the adhesive should be compatible with the elastomer with respect to dynamic mechanical and physical static properties.

B.   Preparation of Surfaces for Bonding

In order to obtain the desired design strength for an elastomer-to-metal bond, it is essential that the substrates be properly prepared. Strict cleanliness of the surfaces to be bonded is important. The proper cleaning procedure will be determined by the substrate and type of contaminant. References 73-75 give general guidelines for proper surface preparation, as well as specific recommendations for given metallic and nonmetallic surfaces. Reference 73 also gives a process control checklist.

Two methods of surface preparation may be used: mechanical and chemical. Mechanical methods involve abrading surfaces with steel wool, a wire brush, or backed abrasives; blasting with sand, grit, or metal oxides; and machining or scoring the surface. Chemical or solvent cleaning may also sometimes have to be employed with mechanical methods. Chemical methods use inorganic or organic reagents to remove soils and surface contamination by chemical action or react with metal surfaces to form metallic compounds.

The choice of the method of cleaning will be influenced by several factors. Chemical treatments are generally less costly than mechanical cleaning. Mechanical methods offer a greater versatility, however, since the same mechanical methods may be applicable to many different metals. Existing facilities may also help to determine whether mechanical or chemical processing is preferred. Environmental resistance requirements may also be important, since chemical methods often give enhanced resistance compared to mechanical cleaning.

Reference 74 gives a complete description of cleaning methods for a large number of metals, alloys, and plastics. Reference 75 also contains information on cleaning methods. It is suggested that the reader consult these for specifics. References 73 and 75 may be obtained upon request from the publisher. In addition, information on a number of commercially available cleaning and processing solutions, along with suppliers' names, may be obtained from the publishers of Ref. 75.

Once an optimum surface has been obtained, it should be maintained until the primer or adhesive is applied. Exposure to dust, moisture, or other contaminants should be avoided. A useful and quick method to check for surface contamination is the water-break test. Distilled water should wet the surface of the substrate in an unbroken film. If this does not occur, either surface contamination has occurred or the surface preparation has been inadequate.

C.   The Bonding Process

The bonding process may involve the bonding of either unvulcanized or vulcanized elastomers to metal. Bonding of metal to vulcanized elastomers is a much more difficult task. There are several reasons for this. Vulcanization of the elastomer gives a cross-linked polymer that has often been compounded to optimize a certain characteristic, such as aging resistance or water permeability resistance. These polymers are difficult to solvate, and it is difficult to obtain any degree of chemical crosslinking between the polymer and the adhesive. Contamination of the elastomer surface with metal release agents, or with plasticizers or antioxidants which have migrated to the surface, make wetting with the adhesive difficult and provide weak boundary layers.

A number of methods for solving these problems are discussed in Ref. 76. Basically, they involve cleaning the surface and then modifying it by either mechanical abrasion or buffing, cyclizing, isocyanate treatment, or chlorination. It is believed that the chemical treatments cause a reversion depolymerization, or oxidation of the elastomer surface [76]. With the possible exception of cyclizing, they slightly increase the surface roughness.

Cyclizing involves the use of various concentrated acids to modify the elastomer surface--sulfuric acid being the most commonly used. Care should be taken not to over-treat the elastomer, as the surface will harden and become brittle.

Isocyanates have also been used as a pretreatment for bonding of vulcanized elastomers, particularly chlorinated ones. References describing the use of isocyanates may be found in Ref. 76.

A chlorine solution is sometimes used to treat vulcanized elastomers in order to improve adhesion to coatings. The following procedure is recommended [76]. A solution consisting of 100 parts by volume water, 3 parts by volume 5.25% sodium hypochlorite solution (Clorox), and 0.5 parts by volume 37% hydrochloric acid is prepared. Alternatively, chlorine gas may be bubbled through water. These solutions should be prepared and used in a well ventilated area.

The vulcanized elastomer is then immersed for 1 to 3 minutes, followed by a rinse in running hot or cold water. The elastomer is then dried in forced air. The immersion time may be varied to suit the particular elastomer. Rubbers with an 80 to 90 Shore A hardness may require more than 3-minutes immersion, while those in the 30 to 40 Shore A range can be treated in 1 minute or less [76]. It may also be necessary to increase the Clorox concentration to 6 volumes per 100 volumes of water for highly filled Neoprene elastomers. The treatment time may also have to be extended to as much as 6 minutes.

A number of commercial systems are now available for bonding vulcanized elastomers to metals. Information on these may be obtained from the manufacturers. A list of adhesives manufacturers is given in Appendix D.

The bonding of an unvulcanized elastomer to a metal takes place in several steps. After the metal surface has been prepared, a suitable primer is applied. A primer is usually necessary for maximum environmental resistance. The primer should be thoroughly dispersed and evenly applied. It should be applied in a thin coat, and completely dried before the first coat of adhesive is applied.

Several different methods may be used to apply the adhesive. Spraying, dipping, brushing, roll coating, tumbling, or any other suitable method may be used. The particular method of application chosen will depend upon the size and shape of the metal parts, the number of pieces to be coated, and whether they are to be completely or partially coated. In any case, the adhesive should be thoroughly agitated prior to and during application. Each part should be coated with a uniform film of sufficient thickness to obtain the desired degree of adhesion. If more than one coat of adhesive is required, sufficient time between applications should be allowed to insure that the solvent from the first coat has completely evaporated.

After application of the adhesive, the metal component is positioned in the mold. Unvulcanized rubber is then placed in the mold so that it contacts the adhesive surface. The normal curing cycle for the elastomer is then initiated. During this time, the primer and adhesive cure by chemical reaction, the elastomer is vulcanized, and a chemical bond is formed between the elastomer and the metal.

During vulcanization, adequate pressure should be applied to the mold. It is also important that the temperature be uniform throughout in multi-cavity molds. Nonuniformity will result in bond failure and overcure or undercure on some parts.

Care should be exercised in any post-bonding treatment. Use of liquid nitrogen in deflashing parts can cause bond failure if the joint is put under stress at a low temperature. Deflashing or cleaning by wire brushing, grinding, or machining may cause problems if excess heat is generated. Other procedures, particularly electroplating, may also cause failure. This may occur if the current density is too high, the adhesive is adversely affected by the plating bath, or the joint is highly stressed while it is being plated.

D.   Bond Failures

A number of procedures for testing adhesive joints are specified by the American Society for Testing and Materials (ASTM). The ASTM also provides a detailed set of sympton descriptions for bond failures.

The ASTM specifications cover the majority of bond failures and are grouped into four basic designations: RC - failure at the elastomer-adhesive interface; CP - failure at the adhesive-primer interface; CM - failure at the metal-primer interface; and R - failure in the elastomers.

The last category can be further broken down to subcategories. Rubber failures may be classified as [73]: SR - Spotty rubber, TR - Thin rubber; HR - Heavy rubber, or SB - Stock break. SR appears on the metal surface looking like splattered rubber. It is usually caused by contamination of the metal surface with dust or other foreign material prior to bonding. It may also be caused by ultrafast drying of the adhesive if it is applied by spraying. TR is an even but very thin residue of elastomer on the metal surface. It usually occurs with rubber stocks that are highly oil extended, as a consequence of migration of oils to the rubber-adhesive interface. HR is a thick layer of rubber remaining on the metal surface and is indicative of an excellent bond. Failure occurs because the elastomer is stressed beyond its cohesive point. SB is a type of failure where it appears that the elastomer has folded back on itself and broken off.

Complete descriptions of other types of bond failures, possible causes, and suggested cures are contained in Ref. 73. This reference also contains photographic illustrations of the results encountered in different types of bond failures. It is suggested that the reader consult Refs. 73 and 74 along with the ASTM standards for further specifics of troubleshooting bond failures.

E.   Commercially Available Systems

A number of adhesive systems are commercially available for bonding elastomers to metals, elastomers to different types of elastomers, and elastomers to plastics. In particular the Thixon Series, manufactured by the Dayton Coatings and Chemicals Div. of the Whittaker Corp. includes adhesives for virtually all types of elastomers. The Chemlok Series, manufactured by Hughson Chemicals, is another complete line of adhesives for different types of rubbers. In addition, Products Research and Chemicals Corp. and Conap, Inc., make lines of primers and adhesives for their polyurethane compounds. Other companies, such as B. F. Goodrich, make general-purpose or specialty adhesives that may be suitable for a given application.

A list of adhesive manufacturers is given in Appendix D. Specific product information and manufacturers' recommended usages may be obtained from companies listed therein.

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APPENDIX A

GENERIC DESIGNATION CROSS INDEX

Generic Designation	Commercial or Trade Name	Manufacturer or Supplier
Acrylic (AM)	Cyanacrils	American Cyanamid
	Hycar 4000 series	B. F. Goodrich
Butadiene (BR)	Cisdenes	American Synthetic
	DIENE's	Firestone
	Duragens	General Tire
	Ameripol CB's	B. F. Goodrich
	Micro-Black CB's	B. F. Goodrich
	Budene 1200 series	Goodyear Chemicals
	Plioflex 5001	Goodyear Chemicals
	JSR BR & RB series	JSR
	Solprene 233	Phillips Chem.
	TAKTENE	POLYSAR
	Synpol E-BR Series	Texas-U. S. Chemical
Chloroprene (CR)	Neoprene TW & WRP	E. I. Dupont
	Neoprene E, M, or S	Petro-Tex Chem.
Ethylene-Propylene (EPM)	Epsyn 7006	Copolymer Rubber
	Epcar 306 & 505	B. F. Goodrich
Ethylene-Propylene-Diene (EPDM)	Epsyns except 7006	Copolymer Rubber
	Nordels	E.I. Dupont
	Epcars except 306 & 505	B. F. Goodrich
	Royalenes	Uniroyal
Fluorocarbon (CFM)	Kalrez & Vitons	E.I. Dupont
	Fluorels	3M Co.
Isobutylene	Vistanex	Exxon
Isobutylene Isoprene (IIR) [Butyl]	Bucars	Cities Service
	POLYSAR Butyls	POLYSAR
Isoprene (IR)	Ameripol SN's	B. F. Goodrich
	Natsyns	Goodyear Chem.
	DPR's	Hardman INC.
	TRANS-PIP's	POLYSAR

Generic Designation	Commercial or Trade Name	Manufacturer or Supplier
Natural Rubber		
Nitrile (NBR)	Nysyn series	Copolymer Rubber
	Nysynblak series	Copolymer Rubber
	Hycar 10XX & 14XX series	B. F. Goodrich
	Hycar Nitrile 1031, 1411,& 1432	B. F. Goodrich
	Chemigum N series	Goodyear Chem.
	CRYNAC series up to 810 & 843	POLYSAR
	Paracril A, B, C, D, & J series	Uniroyal
	Paracril 1880, 1880LM,3300 & 4304	"
Polysulfides (T)	FA series	Thiokol Chemicals
Polyurethanes (U)	Adiprenes	E. I. DuPont
	Andur series	Anderson Dev.
	Arcon series	Allied Resin Corp.
	Calthane series	Cal Polymers
	Castathane series	Upjohn Co.
	Castomer series	Witco
	CONAP series	CONAP Inc.
	CONATHANE series	CONAP Inc.
	Curene series	Anderson Dev.
	Cyanaprene series	American Cyanamid
	Diosogrin series	Diosogrin
	Multrathane	Mobuy
Silicones (MQ)	G. E. Silicones	General Electric
	Rhodorsil series	Rhodia
	Silastic series	Dow Corning
	SWS series	SWS silicones
Styrene-butadiene (SBR)	Ameripol Numbered series	B. F. Goodrich
	ASRC series	American Synthetic
	Baytown series	Ashland Chemical Co.
	Carbomix series	Copolymer Rubber
	Cold Microblack series	B. F. Goodrich
	COPO series	Copolymer Rubber
	FR series	Firestone
	Kraton series	Shell
	Krylene series	Polysar
	Plioflex series	Goodyear Chemicals
	Synpol series	Texas U. S. Chem. Co.

APPENDIX B

COMMERCIAL NAME CROSS INDEX

Commercial or Trade Name	Generic Designation	Manufacturer or Supplier
Adiprenes	Polyurethane (U)	E.I. Dupont
Ameripol CB series	Butadiene (BR)	B. F. Goodrich
Ameripol SN series	Isoprene (IR)	B. F. Goodrich
Ameripol Numbered series	Styrene-butadiene (SBR)	B. F. Goodrich
Andur series	Polyurethane (U)	Anderson Dev.
Arcon series	Polyurethane (U)	Allied Resin Corp.
ASRC series	Styrene-butadiene (SBR)	American Synthetic
Baytown series	Styrene-butadiene (SBR)	Ashland Chem. Co.
BUCAR series	Isobutylene-isoprene (IIR)	Cities Service Co.
Budene series	Butadiene (BR)	Gem. Co.
Calthane series	Polyurethane (U)	Cal Polymers
Carbomix series	Styrene-butadiene (SBR)	Copolymer Rubber
Castathane series	Polyurethane (U)	Upjohn Co.
Castomer series	Polyurethane (U)	Witco
Catapol series	Polyurethane (U)	Arnco
Catapol series	Polyurethane (U)	Arnco
Chemigum series	Nitrile (NBR)	Goodyear Chem.
Cisdene	Butadiene (BR)	American Synthetic
Cold Microblack series	Styrene-butadiene (SBR)	B. F. Goodrich
CONAP series	Polyurethane (U)	Conap Inc.

(continued)

Commercial or Trade Name	Generic Designation	Manufacturer or Supplier
CONATHANE series	Polyurethane (U)	Conap Inc.
COPO series	Styrene-butadiene (SBR)	Copolymer Rubber
Curene series	Polyurethane (U)	Anderson Dev.
Cyanacryl series	Acrylic (AM)	American Cyanamid
Cyanaprene series	Polyurethane (U)	American Cyanamid
DIENE series	Butadiene (BR)	Firestone
Diosogrin series	Polyurethane (U)	Diosogrin
DPR series	Isoprene (IR)	B. F. Goodrich
Duragen series	Butadiene (BR)	General Tire
Epcar series (except 306 & 505)	Ethylene – Propylene – Diene (EPDM)	B. F. Goodrich
Epcar 306 & 505	Ethylene – Propylene (EPR)	B. F. Goodrich
Epsyn series (except 7006)	Ethylene – Propylene (EPR) Diene (EPDM)	Copolymer Rubber
Epsyn 7006	Ethylene – Propylene (EPR)	Copolymer Rubber
FA-3000 series	Polysulfide rubber (T)	Thiokol Chemical
Fluorel series	Fluorocarbon (CFM)	3M Co.
FRS series	Styrene-butadiene (SBR)	Firestone
G. E. Silicones	RTV silicones	General Electric
Gentro series	Styrene-butadiene (SBR)	General Tire
Hycar 4000 series	Acrylic (AM)	B. F. Goodrich
Hycar Nitriles	Nitrile (NBR)	B. F. Goodrich
Hypalon	Chlorosulfonated Polyethylene	E. I. DuPont
JSR BR & RB series	Butadiene (BR)	J.SR.
Kalrez series	Fluorocarbon (CFM)	E. I. DuPont
Kel-F series	Fluorocarbon (CMF)	3M Co.

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Commercial or Trade Name	Generic Designation	Manufacturer or Supplier
Kraton series	Styrene-butadiene (SBR)	Shell
Krylene series	Styrene-butadiene (SBR)	POLYSAR
Multrathane F series	Polyurethane (U)	Mobay Chem. Co.
Neoprene series	Polychloroprene	E. I. DuPont
Nordel series	Ethylene - Propylene - Diene (EPDM)	E. I. DuPont
Nysyn series	Nitrile (NBR)	Copolymer Rubber
Nysyn blak series	Nitrile (NBR)	Copolymer Rubber
Paracril series	Nitrile (NBR)	Uniroyal
Plioflex series	Styrene-butadiene (SBR)	Goodyear Chem.
POLYSAR Butyls	Isobutylene-Isoprene (ITR)	POLYSAR
Rhodorsil series	Silicone (MO)	Rhodia
Royalene series	Ethylene - Propylene - Diene (EPDM)	Uniroyal
Silastic series	Silicone	Dow Corning
Solprene 233	Butadiene (BR)	Phillips Chem.
SWS series	Silicone (MO)	SWS silicones
Synpol E-BR series	Butadiene (BR)	Texas U.S. Chem.
TAKTENE	Butadiene (BR)	POLYSAR
Vibrathane	Polyurethane	Uniroyal
Viton	Fluorocarbon (CFM)	E. I. DuPont

APPENDIX C

MANUFACTURERS OR SUPPLIERS INDEX

AGI Rubber Co.
135-A Stratford Avenue
Bridgeport, CT   06608
(203) 366-4318

Allied Resin Corp.
Weymouth Industrial Park
East Weymouth, MA   02189
(617) 337-6070

American Cyanamid Co.
Bound Brook, NJ   08805
(201) 356-2000

American Synthetic Rubber Co.
P. O. Box 360
Louisville, KY   40201
(504) 448-2761

Anderson Development Co.
1415 E. Michigan Street
Adrian, MI   49221
(517) 263-2121

Arnco
4676 Admirality Way
Suite 1034
Marina Del Ray, CA   90291
(213) 822-5282

Ashland Chemical Co.
P. O. Box 2219
Columbus, OH   43216
(614) 889-3333

BASF Wyandotte Corp.
Wyandotte, MI   48192
(313) 292-3300

Buckeye Rubber Products
777 Benra Street
Lima, OH   45802
(419) 228-4441

Burke Rubber Co.
2250 S. 10th St. at Burke
San Jose, CA   95112
(408) 297-3500

Cal Polymers Inc.
2115 Gaylord St.
Long Beach, CA   90813
(213) 436-7372

Cities Service Co.
Columbian Division
3200 W. Market St.
Fairlawn Village
Akron, OH   44313
(216) 867-5800

Conap Inc.
1405 Buffalo St.
Olean, NY   14760
(716) 372-9650

Copolymer Rubber and Chemical Co.
P. O. Box 2591
Baton Rouge, LA   70821
1-800-535-9960

Diosogrin Industries Corp.
Grenier Field
Manchester, NH   03103
(603) 669-4050

(continued)

E. I. DuPont de Nemours and Co.
1007 Market Street
Wilmington, DE   19898
(302) 774-2421

Emerson and Cuming Inc.
869 Washington Street
Canton, MA   02021

Firestone Synthetic Rubber & Latex Co.
1200 Parkstone Pkwy.
Akron, OH   44317
(216) 379-7000

Garrett Flexible Products Inc.
1101 S. Cowen Street
Garrett, IN
(219) 357-4130

General Electric
Silicone Products Department
Waterford, NY   12188
(518) 237-3330)

General Tire & Rubber Co.
1 General Street
Akron, OH   44329
(216) 798-3000

B. F. Goodrich Chemical Co.
6100 Oak Tree Blvd.
Cleveland, OH   44131
(216) 794-2121

Goodyear Tire and Rubber Co.
Rubber Division
P. O. Box 9023
Akron, OH
(216) 524-0200

Hardman, Inc.
Belleville, N. J.
(201) 751-3000

Huntington Rubber Co.
P. O. Box 570
Portland. OR   97207
(503) 246-5411

Isochem Resins Co.
99 Cook Street
Lincoln, RI   02865
(401) 723-2100

Jacobs Rubber Co.
101 Lake Road
Dayville, CN
(203) 774-9611

Jasper Rubber Co.
Jasper, Georgia
(404) 692-2417

JSR America, Inc.
350 Fifth Sve.
Suite 8001
New York, NY   10001

Karmon Rubber Co.
2333 Copley Road
Akron, OH   44320
(216) 864-2161

Kirkhill Rubber Co.
Cypress Court
Brea, CA
(714) 529-4901

Master Processing Corp.
2502 Thompson Street
Long Beach, CA   90805
(213) 531-3880

Mobay Chemical Corp.
Polyurethane Division
Pittsburgh, PA   15205
(412) 923-2700

Paramount Packing & Rubber, Inc.
4018 Belle Grove Road
Baltimore, MD
(301) 789-2236

Pawling Rubber Corp.
157-A Maple Blvd.
Pawling, NY   12564
(914) 855-1000

Pelmor Laboratories, Inc.
400 Lafayette St.
Newton, PA 18940
(214) 963-3825

Petro-Tex Chemical Co.
8600 Park Place Blvd.
Houston, TX 77017
(713) 477-9211

Phillips Chemicals
Division of Phillips Petroleum Co.
Internation Department
1501 Commerce Drive
Stow, OH 44224
(216) 688-6652

Polysar International
1795 West Market St.
Akron, OH 44313
(262) 836-0451

Precision Associates, Inc.
742 N. Washington Ave.
Minneapolis, MN 55401
(612) 336-8394

Products Research & Chemical Corp.
5454 San Fernando Rd.
P. O. Box 1800
Glendale, CA 92109
(213) 240-2060

Rhodia, Inc.
P. O. Box 125
Monmouth Junction, NJ 08852
(201) 846-7700

Rubber Corporation of America
2535 N. Broad Street
Philadelphia, PA 19132
9215) 225-3700

Rubber Crafters Inc.
P. O. Box 356
South Plainfield, NJ
(201) 754-8100

Salem Republic Rubber Co.
California & 19th Street
Sebring, OH 44672
(216) 938-9801

Shell Chemical Co.
One Shell Plaza
Houston, TX 77002
(713) 220-6161

Sperry Rubber Plastics Co.
31 W. Thomas Street
Brookville, IN
(317) 647-4141

Star-Glo Industries, Inc.
4 Carlton Ave.
East Rutherford, NJ 07073
(201) 939-6162

SWS Silicones Corp.
Division of Stauffer Chemical Co.
Adrian, MI 49221
(517) 263-5711

Texas-U. S. Chemical Co.
One Greenwich Plaza
Greenwich, CT 06830
(203) 661-3050

Thiokol/Chemical Division
930 Lower Ferry Road
Trenton, NJ 08607
(609) 396-4001

3M Company
Commercial Chemicals Division
3M Center
St. Paul, MN 55101
(612) 733-1110

Uniroyal Chemicals Division
Division of Uniroyal, Inc.
Elm Street
Naugutuck, CT 06770
(203) 723-3000

Unirubber Inc.
130-A East 35 Street
New York, NY 10016
(212) 685-0200

Upjohn Company
CPR Division
555 Alaska Avenue
Torrance, CA 90503
(213) 320-3550

William-Bowman Rubber Co.
1945 S. 54th Avenue
Cicero, IL 60650
(312) 242-1640

Witco Chemical Co.
Organic Division
400 N. Michigan Ave.
Chicago, IL 60611
(312) 644-7200

APPENDIX D

MANUFACTURERS OF ADHESIVES

Adchem Corporation
625 Main Street
Westbury, NY   11590
516-333-3843

Adhesive Products Inc.
520 Cleveland Ave.
Albany, CA   94710
212-542-4600

Adhesives Research Inc.
161 E. Ninth Ave.
York, PA   17404
717-235-4860

Alco Chemical Corp.
Trenton Ave. & Williams St.
Philadelphia, PA   19134
215-425-0621

Allaco Products
130 Wood Rd.
Braintree, MA   02184
617-926-2550

Allen Products Corp.
9214 Livernois Ave.
Detroit, Michigan 48204
313-924-7400

Allied Adhesive Corp.
91-20-130th St.
Richmond Hill, NY   11418
212-846-3200

American Cyanamid Co.
Ind. Chemical Div.
Berdan Ave.
Wayne, NJ   07470
201-831-1234

American Metaseal Co.
509 Washington Ave.
Carlstadt, NJ   07072
201-933-1720

Applied Plastics Co. Inc.
130 Penn St.
El Segundo, CA   90245
213-322-8050

Argo Paint and Chemical Co.
19440 Fitzpatrick St.
Detroit, MI   48228
313-729-7400

Armstrong Products Co. Inc.
Argonne Rd.
Warsaw, Ind. 46580
219-267-3226

Atlantic Paste & Glue Co.
9 53rd St.
Brooklyn, NY   11232
212-492-3648

Atlas Minerals & Chemicals Div.
ESB Inc.
Mertztown, PA   19539
215-682-7171

BFC Division
Essex Chemical Corporation
1401 Broad St.
Clifton, NJ   07012
201-773-6300

Baker Sealants & Coatings Co.
234 Suydam Ave.
Jersey City, NJ   07304
201-333-6986

(continued)

221

Baltimore Adhesive Co.
Reisterstown Rd.
Owings Mills, MD   21117
301-363-0177

Burker Chemical Co.
700 E. 138th St.
Chicago, IL   60627
312-995-9600

Bay State Adhesive Corp.
So. Mason St.
Salem, MA   01970
617-744-8237

Berco Industries Corp.
1250 Shames Dr.
Westbury, NY   11590
516-334-4222

Bond Adhesives Co.
120 Johnston Ave.
Jersey City, NJ   07303
201-243-8100

Burrage Glue Co.
91-20 130th St.
Richmond Hill, NY   11418
212-846-1600

Calopolymers Inc.
2115 Gaylord St.
Long Beach, CA   90813
213-436-7372

Can-Tite Rubber Corp.
33 Redfern Ave.
Inwood, NY   11696
212-327-2800

Carboline Co.
328 Hanley Ind. Court
St. Louis, MO   63144
314-644-1000

Cat's Paw Rubber Co.
Warner & Ostend Sts.
Baltimore, MD   21230
617-884-1700

Cementex Co. Inc.
336 Canal St.
New York, NY   10013
212-226-5832

Chemical Seal Corp. of America
598 West Ave. 26
Los Angeles, CA   90065
213-982-1655

Chemical Coatings & Eng. Co.
221 Brooks St.
Media, PA   19063
215-566-7470

Chemical Sealing Corp.
5401 Banks Ave.
Kansas City, MO   64130
816-923-8812

Chicago Adhesive Products Co.
4658 W. 60th St.
Chicago, IL   60629
312-581-1300

Chrysler Corporation
Chemical Division
5437 Jefferson St.
Trenton, Michigan   48183
312-956-5741

Clifton Adhesive Inc.
Burgess Place
Wayne, NJ   07470
201-694-0845

Commercial Chemical Co.
1021 Summer St.
Cincinnati, Ohio   45204
513-921-8600

Conap Inc.
184 E. Union St.
Allegany, NY   14706
716-372-9650

Contact Industries Inc.
850 S. Oyster Bay Rd.
Hicksville, NY   11801
201-351-5900

(continued)

222

Conwed Corp.
2200 Highcrest St.
St. Paul, Minn. 55113
612-221-1100

Peter Cooper Corp.
Palmer St.
Gowanda, NY 14070
716-532-3344

DAP Inc.
5300 Huberville Rd.
Dayton, Ohio 45431
513-253-7151

Dow Corning Corp.
Midland, Michigan 48640
517-496-4000

E. I. DuPont de Nemours & Co.
1007 Market St.
Wilmington, Del. 19898
302-774-2421

Epoxylite Corp.
1901 Via Burton
Anaheim, CA 92806
714-630-7910

Fel-Pro Inc.
7450 N. Mc Cormick Blvd.
Skokie, Illinois 60076
312-674-7700

Findley Adhesives Inc.
3033 W. Pemberton Ave.
Milwaukee, Wisconsin 53245
414-782-2250

Firestone Tire and Rubber Co.
1200 Firestone Parkway
Akron, Ohio 44317
216-379-7000

Flexcraft Industries, Inc.
527 Ave. P
Newark, NJ 07105
201-589-3403

Benjamin Foster Div.
Amchem Products Inc.
Brookside Ave.
Ambler, PA 19002
215-628-7000

Franklin Glue Co.
2020 Beuck St.
Columbus, Ohio 43207
614-443-0241

Gates Eng. Div., SCM Corp.
100 S. West St.
Wilmington, Del. 19899
302-656-9951

General Adhesives & Chem. Co.
6100 Centennial Blvd.
Nashville, TN 37209
615-367-6833

Gilsonite Co.
2946 Northeast Columbia Blvd.
Portland, Oregon 97211
503-288-5454

B. F. Goodrich Ind. Prod. Co.
Adhesive Prod. Div.
500 S. Main St.
Akron, Ohio 44318
216-379-2000

Goodyear Tire & Rubber Co.
Chemical Div.
1485 E. Archwood Ave.
Akron, Ohio 44316
216-794-3010

Holt Mfg. Co. Inc.
2615 Fifth Ave. S.
Birmingham, Alabama 35233
205-956-3789

Hughson Chemical Co.
2000 W. Grandview Blvd.
Erie, PA 16509
313-588-1500

(continued)

223

ICI America Inc.
151 South St.
Stamford, CT 06904
302-575-3000

Imperial Adhesives & Chemicals Inc.
6315 Wiehe Rd.
Cincinnati, Ohio 45237
513-841-4545

Industrial Polychemical Service
17116 S. Broadway
Gardena, CA 90247
213-321-6515

Isochem Resins Co.
99 Cook St.
Lincoln, RI 02865
401-723-2100

Jones Chemical Co.
1230 Harry Hines Blvd.
Dallas, TX 75234
214-661-5425

Key Polymer Corp.
275 Lowell St.
Lawrence, MA 01842
617-683-9411

H. B. Fred Kuhls Co.
49 Sumner St.
Milford, MA 01757
617-473-3424

Loctite corp.
705 N. Mountain Rd.
Newington, CT 06111
800-243-8810

Minnesota Mining & Mfg. Co. (3M)
3M Center
St. Paul, Minn. 55101
612-733-1110

Narmco Materials Div.
Whittaker Corp.
600 Victoria St.
Costa Mesa, CA 92627
714-548-1144

National Starch & Chem. Corp.
750 Third St.
New York, NY 10017
201-685-5000

Ohio Sealer Div.
NDM Corporation
3040 East River Rd.
Dayton, Ohio 45439
513-294-1767

PPG Industries
225 Belleville Ave.
Bloomfield, NJ 07003
412-434-3131

Pemco Adhesives, Inc.
West Township Rd.
Auburn, Ind. 46706
219-925-3368

Pierce & Stevens Ch.m. Corp.
710 Ohio St.
Buffalo, NY 14203
716-856-4910

Pilot Chemical Co. Inc.
10-30 Jackson Ave.
Long Island City, NY 11101
212-729-8282

Polymer Chemical Co.
131 Barron Dr.
Cincinnati, Ohio 45215
513-771-6324

Presto Adhesives, Inc.
5436 W. Rogers St.
West Allis, Wis. 53219
414-327-3450

Products Research & Chem. Corp.
2919 Empire Ave.
Burbank, CA 91504
213-240-2060

Radioptics, Inc.
10 Dupont St.
Plainview, NY   11803
516-935-3050

Raybestos-Manhattan Inc.
75 E. Main St.
Stratford, CT   06601
203-371-0101

Research Sales Inc.
Route 202 & Ramapo Ave.
Mahwah, NJ   07430
201-529-3676

Roberts Consolidated Ind. Inc.
600 E. Evergreen Rd.
Monrovia, CA   91016
212-422-4170

Patrick Ross Co.
619 Somerville Ave.
Somerville, MA   02141
617-354-8100

Rubba, Inc.
1015 E. 173rd St.
Bronx, NY   10460
212-542-4661

Rubber Latex Co. or America
210 Delawanna Ave.
Clifton, NJ   07014
201-473-3020

Ruco Div. Hooker Chemical Co.
New South Rd.
Hicksville, NY   11802
609-499-2300

Service Adhesives Co. Inc.
1214 S. 6th St.
Maywood, ILL   60153
312-681-5751

Shuford Mills Inc.
Highland Ave. & 15th St.
Hickory, NC   28601
704-322-2700

Smooth-On, Inc.
1000 Valley Rd.
Gillette, NJ   07933
201-647-5800

Southern Adhesives Corp.
4105 Castlewood Rd.
Richmond, VA   23234
513-561-8440

Sta-Bond Corp.
14101 S. Western Ave.
Gardena, CA   90249
213-770-0591

Sta-Crete Inc.
893 Folsom St.
San Francisco, CA   94107
213-968-6511

Standard Paste & Glue Co.
3624 W. 38th St.
Chicago, IL   60632
312-523-1412

Sullivan Chemicals Div.
Sullivan Varnish Co.
420 N. Hart St.
Chicago, IL   60622
312-666-8080

Testworth Laboratories Inc.
139 Commercial Rd.
Addison, Ill 60101
219-244-5137

Thiokol Chemical Corp.
930 Lower Ferry Rd.
Trenton, NJ   08607
609-396-4001

USM Corp., Chemical Div.
Middleton, MA   01949
617-777-0100

Uniroyal Inc.
Adhesives & Coatings Dept.
312 North Hill
Mishawaka, Ind. 46544
219-255-2181

Uniroyal Chemical Div.
Uniroyal Inc.
Elm St.
Naugatuck, CT 06770
203-723-3000

Uniseal Inc.
1181 Diamond Ave.
Evansville, Ind. 47711
812-425-1361

United Resin Products, Inc.
100 Button St.
Brooklyn, NY 11222
212-384-3000

U. S. ADhesives Co.
1735 W. Carroll Ave.
Chicago, IL 60612
312-829-7438

U. S. Gypsum Co.
101 S. Wacker Dr.
Chicago, IL 60606
312-321-4000

Virginia Adhesives Corp.
1920 Rose Lane
Lynchburg, VA 24505
804-846-1466

West Chester Chem. Co.
439 S. Bolmar St.
West Chester, PA 19380
215-696-9220

Whittaker Corp.
10 South Electric St.
P. O. Box 27
West Alexandria, OH 45381
513-839-4612
513-835-5656

Williamson Adhesives Inc.
8220 Kimball Ave.
Skokie, IL 60076
312-673-6890

Abrasion Resistance (ASTM D1630-61 - D2228-69) - This refers to the resistance of an elastomer to wear and is usually measured by the amount of material lost when placed in contact with a moving abrasive surface. It is given as a volume-loss percentage when compared to a standard elastomer. A quantitative result is very difficult to obtain, and most elastomers are classified as poor, fair, good, or excellent.

Acoustic Impedance - The propagation of acoustic waves into and through a material depends on the density of the material and the speed of the acoustic waves within the material. The product of density and acoustic speed for a certain material is termed the specific acoustic impedance. Acoustic impedance is also the characteristic property that governs sound transmission from one medium to another, as from a liquid into a solid. The greater the impedance mismatch between two media the lower will be the transmission of an acoustic wave from one to the other. Practically speaking, the impedance mismatch between transducer elastomers and fluids is not usually a critical factor in the audio-frequency and low ultrasonic range. This will, of course, depend upon the geometry and stiffness of the material. However, for transducers operating at higher frequencies, the acoustic impedance of a window material is an important consideration.

The speed of an acoustic wave in a material is directly proportional to the square root of the governing modulus. The governing modulus is the modulus associated with the particular mode of wave propagation; i.e., shear modulus (G) governs the propagation of shear waves while the bulk modulus (K) and the longitudinal modulus (M) govern the propagation of bulk and plane waves, respectively. The relationship between modulus and acoustic velocity is given by $R = \rho(\overset{*}{c})^2$ where R represents a generic modulus, ρ is material density, and $\overset{*}{c}$ is acoustic velocity.

Dielectric Strength (ASTM D149-75) - This is the ability of a dielectric material to separate charges of a potential difference. It is the ratio of breakdown voltage to sample thickness.

Electric Dissipation Factor (ASTM D150-74) - This is the ratio of the parallel reactance to the parallel resistance. It is related to the energy dissipated and, therefore, to the efficiency for insulating materials.

Hardness (ASTM D2240-75) - This is an indication of the resistance of an elastomer to deformation. It is determined by pressing a ball or rounded tool into the surface of the elastomer. The resistance is measured on various scales covering very soft elastomers to very hard ones. These measurements are designated by a Shore Hardness scale of A or D and given values of 0 to 100 within each scale. Shore A is used for soft elastomers and Shore D for hard elastomers.

Low-Temperature Stiffness (ASTM D832-77 - D1053-75) - The low-temperature stiffening point is the temperature at which Young's modulus reaches 10,000 psi or 68.9 MPa. In general, the softer the material, the lower the stiffening temperature will be.

Ozone Resistance (ASTM D3395-75 - D1149-77) - This is the resistance of elastomeric materials to cracking and oxidation under high atmospheric ozone concentrations. This property is indicative of the ability of a material to exist in a high corona environment without exhibiting extensive oxidative degradation.

Relative Dielectric Constant (ASTM D150-75) - This is the ratio of the dielectric constant of the material ϵ_m to that of free space ϵ_o. It is usually measured by determining the parallel-plate-capacitance with the material between the plates C_m and the capacitance with a vacuum between the plates C_o.

Tensile Strength (ASTM 638-77) - In elastomers this refers to the force per unit of original cross-sectional area required to elongate to rupture.

300% Modulus (ASTM D638-77) - (Tensile stress at given elongation.) In elastomers this refers to the force per unit of original cross-sectional area to produce a total extension of 300%. Other elongations have also been used. It is a ratio of the stress applied to the strain induced but is not a measure of Young's modulus. It is also not related to hardness.

Ultimate Elongation (ASTM D638-77) - This is the maximum extension in percent of an elastomer at the instant of rupture.

Vapor Pressure (ASTM D323-72 - D2551-71) - This is the absolute pressure exerted by a vapor in equilibrium above a solid or liquid.

Viscosity (ASTM D1646-74) - This is the resistance of fluids to a change of form. It is expressed in Pascal-seconds.

Volume Resistivity (ASTM D991-75) - This is the resistance to current leakage through the sample.

Water Permeability (ASTM E96) - This is the rate at which water molecules will be transmitted through a sample after it has stabilized between fluids. It is measured by determining the mass of water passing through the sample per unit area, unit time, and differential water-vapor-pressure per unit thickness (gH_2O cm)/($cm^2 \cdot hr \cdot torr$). (See Table 10 for conversion to other units.)

Table 10 — Conversion Factors for Permeability*

To obtain values expressed in:	From values expressed in cc (STP) mm/cm^2 sec cm Hg, multiply by:
cc mm/cm^2 sec atm	76
cc mil/100 in.^{2} 24 hr. atm	1.67×10^{11}
cu. in. mil/100 in.^{2} 24 hr. atm	1.018×10^{10}
cc mm/100 in.^{2} 24 hr. atm	6.57×10^{12}
cc cm/cm^2 sec torr	10^{-8}
cc mil/m^2 24 hr. atm	2.58×10^{13}
gram water cm/cm^2 hr. torr	34.57

*Taken from Ref. 7

LIST OF SYMBOLS

a_T – The ratio of relaxation times for an elastomer at some temperature T and a temperature T_R which is a characteristic temperature for the material under examination.

α – Attenuation per unit length, nepers/m

c – Sound speed in a given material, m/s

E^* – Complex dynamic Young's modulus, Pa

G^* – Complex dynamic shear modulus, Pa

K^* – Complex dynamic bulk modulus, Pa

M^* – Complex dynamic longitudinal modulus, Pa

R^* – Symbol for a generic complex modulus

ρ – Density of a given material, kg/m^3

$\tan \delta$ – Mechanical loss factor; given as the ratio of loss modulus to storage modulus

ω – Circular frequency, rad/s